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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

APRIL 1924

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THE
ASTROPHYSICAL JOURNAL
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LIFE OF METASTABLE HELIUM

By FABIAN M. KANNENSTINE

ABSTRACT

Dependence of critical 4.8-volt striking frequency on pressure.—The critical 4.8-volt striking frequency for alternating helium arcs was obtained under improved experimental conditions for pressures from 0.15 mm to 10 mm. The critical frequency decreased rapidly from 260 cycles per second at 0.15 mm pressure to 120 cycles at c.75 mm, more slowly to 70 cycles at 2 mm, and remained practically constant at 70 cycles to 10 mm. The critical frequency increased very slightly as the arc-length decreased from 30 mm to 10 mm for pressures below 3.5 mm, but was practically independent of the arc-length used for pressures above 3.5 mm and up to 10 mm.

Interpretation of results on the concept of a long-lived abnormal helium atom.—The constancy of the critical frequency over a large range of pressures and arc-lengths is more naturally interpreted on the concept of a long-lived, abnormal atom than on ideas which suggest a strong dependence on pressure such as the handing on of radiation or the imprisonment of radiation as suggested by F. Horton and Ann C. Davies, and by K. T. Compton. The departure from constancy at low pressures may be interpreted as due to such rapid diffusion of abnormal atoms from the arc space that higher frequencies are necessary to obtain an indication of striking.

INTRODUCTION

In a previous paper[1] experiments with helium arcs were described, in one series of which the current-voltage characteristic with an alternating e.m.f. impressed on the arc was studied. A critical frequency between 200 and 220 cycles per second was found, below which the arc struck at about 25 volts and above which the arc struck at about 4 volts. These results were interpreted on the idea advanced by Franck and Reiche[2] and Franck

[1] *Astrophysical Journal* **55**, 345, 1922.

[2] *Zeitschrift für Physik*, **1**, 54, 1920.

and Knipping[1] that the partially ionized state formed when the helium atom has been excited by the impact of 20.5-volt electrons is a "metastable" state which may persist for some time and may be even permanently stable in absolutely pure helium. This conclusion is drawn from the fact that the radiation observed with electron impacts at this voltage disappeared when the helium was very pure, indicating that the displaced electrons do not return to the normal form. In slightly impure helium they also observed that the radiation, as measured by its photo-effect, appeared to continue for a brief time after the exciting electron impacts ceased. The striking of the arc at about 4 volts with 220 cycles per second indicates that enough of the metastable helium was left, after approximately one-half of a cycle, to give an observable indication of ionization.

F. Horton and Ann C. Davies[2] and K. T. Compton[3] have advanced another interpretation of the striking of the arc at about 4 volts. They assume that the abnormal atoms revert to normal atoms in a very short time—of the order of magnitude of the duration of light emission—with the emission of light, which being absorbed by normal atoms puts them in the abnormal state. These abnormal atoms in turn revert to normal atoms giving up their energy which is again absorbed. This handing on of the radiation from atom to atom goes on until the energy escapes from the arc space. These authors contend that $\frac{1}{440}$ of a second referred to above was not a measure of the life of the individual abnormal atom, but a measure of the time of "escape" of the radiation from the arc space during which many absorptions and re-emissions occur.

Bohr's theory, however, together with the selection principle, indicates that electron jumps from the crossed to the coplanor states do not occur with monochromatic light emission, and this is experimentally confirmed by the absence of combination lines between the two helium series. As long as the selection principle holds, the metastable atom cannot go directly back to the normal state with monochromatic light emission. Violations of the selec-

[1] *Zeitschrift für Physik*, **1**, 320, 1920.

[2] *Philosophical Magazine*, **44**, 1140, 1922.

[3] *Ibid.*, **45**, 750, 1923.

tion principle may be brought about by strong momentary fields. In absolutely pure helium then, neglecting the effects at the walls and the electrodes, the abnormal atom would appear permanently stable, for at a collision with a normal helium atom there would merely be the possibility of an exchange of energy between the abnormal and the normal atom; experimentally, we may have no evidence of this exchange. At a collision with an impurity, strong momentary fields would again come into play and the abnormal atom would return to the normal form.

Experiments by Paschen,[1] which show that in pure excited helium resonance radiation may be caused by the infra-red line 10830 A, also support the concept of a metastable state. All the energy of this wave-length absorbed by the excited atoms was found to be re-emitted as radiation of this same wave-length. In terms of Bohr's model this means that the radiation is absorbed by atoms which have already absorbed the energy corresponding to the radiating potential, 20.5 volts, and that the displaced electrons return to this partially ionized state only, and not to the normal state.

This paper is a report of further experiments with helium arcs, in which, under improved experimental conditions, data are secured which seem to strengthen the concept of a long-lived atom, and in which it has been possible to obtain a life as long as approximately $\frac{1}{140}$ of a second.

EXPERIMENTAL PROCEDURE

The arcs were formed between a Wehnelt cathode and nickel disk anode in a pyrex tube 8 cm in diameter. The current-voltage characteristics of the arc were studied by the use of a sensitive Braun tube oscillograph. The electrostatic deflecting plates of the Braun tube were connected across the electrodes of the helium tube, while the arc current passed through the electromagnetic deflecting coils. The electrostatic and electromagnetic deflections were at right angles, so that the figure on the screen of the Braun tube was a graph in rectangular co-ordinates of the impressed e.m.f. and the arc current. The deflecting coils were

[1] *Annalen der Physik*, **45**, 625, 1914.

so adjusted that the thermionic current alone did not produce any observable deflection.

In the previous experiments the helium had been carefully purified with charcoal immersed in liquid air and heated copper oxide, and had been passed through two additional charcoal tubes and a liquid-air trap before passing into the experimental tube. During the observations the gas was stagnant in the experimental tube and the removal of any impurities given out by the parts of the experimental tube were taken up by diffusion to the connected charcoal tubes. The tube and liquid-air trap had been baked out at 450° C. for several days before the helium was admitted.

In the new experiments, in order to obtain helium of greater purity, the gas, previously purified with charcoal and copper oxide, was circulated through the experimental tube by a mercury vapor pump. To prevent mercury from entering the experimental tube, the entrance and exit of both the diffusion pump and the experimental tube were protected with liquid-air traps. Three charcoal tubes were placed in the circulatory system, two at the entrance and one at the exit of the experimental tube.

The filaments used in the first experiments were prepared by coating a platinum strip with the oxides of barium and strontium. At the time we thought these filaments were fairly active, but Dr. H. Rossbacher and Mr. E. E. Rosaire, of the Western Electric Co., Inc., very kindly prepared some coated filaments for these experiments, which were enormously more active than the coated ones used in the first experiments.

Figures 1 and 2 show the type of figure observed under the old conditions. In the case of Figure 1, the arc was excited with 60 cycles per second taken from the city mains, from which a large amount of energy was available. It is seen that at a certain voltage the arc strikes, and as the voltage increases the current increases also. When the voltage decreases, the current decreases at the same time, but continues with considerable magnitude until the voltage reaches a value of about 4 volts, when the current ceases to flow. This continuation of the arc to very low potentials was attributed to the persistence of a metastable form of helium in which an arc may be maintained down to about 4 volts.

For frequencies above 60 cycles per second use had been made of two borrowed vacuum tube oscillators, and Figure 2 shows the type of figure observed above 220 cycles per second with these oscillators. The arc struck at about 4 volts, and the current rapidly attained a saturation value at which the arc current continued until the voltage had reached about 25 volts, when a second sudden increase was obtained. The decreasing part of the curve was above the increasing part, but fell to zero at the lower striking voltage.

With 200 cycles per second no appreciable arc formation at the lower voltage was observed, indicating that the metastable helium

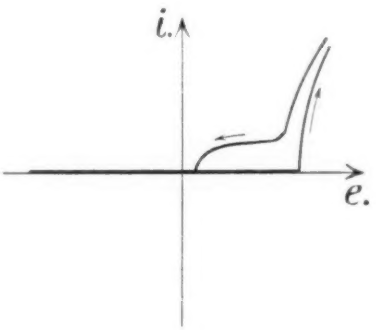

FIG. 1

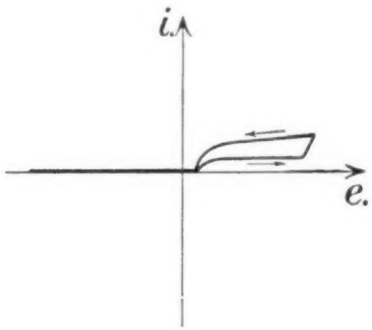

FIG. 2

practically disappeared in less than approximately $\frac{1}{400}$ of a second. The striking of the arc at about 4 volts with 220 cycles per second indicated that enough of the metastable helium was left after approximately $\frac{1}{440}$ of a second to give an observable indication of ionization. The lowest frequency which causes an observable indication of ionization at about 4 volts we will call the "critical frequency."

It will be observed in Figure 2 that after the higher striking potential has been reached, very little increase of the voltage and only a small increase of the ionization current occurs, while with 60 cycles per second a very large ionization current is obtained at the higher striking potential. This difference in the figures is due to the voltage characteristic of the sources of e.m.f. At 60 cycles per second a large amount of energy was available and the

voltage was practically independent of the load, while with the vacuum tube oscillators used the voltage decreased rapidly as the current increased.

To eliminate the objections to this falling-voltage characteristic, a new vacuum tube oscillator was constructed having considerable energy output. The circuit was so arranged that the output of the oscillator could be controlled and so that any changes in the load conditions did not affect the frequency.

OBSERVATIONS

Under these new conditions figures similar to Figure 1 could be obtained just below the critical frequency. As the frequency was gradually increased ionization at about 4 volts suddenly occurred,

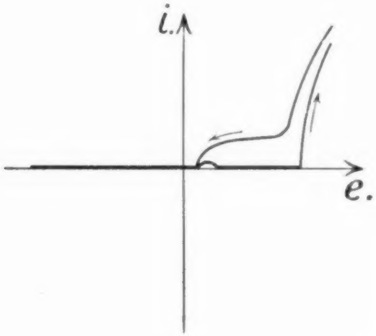

Fig. 3

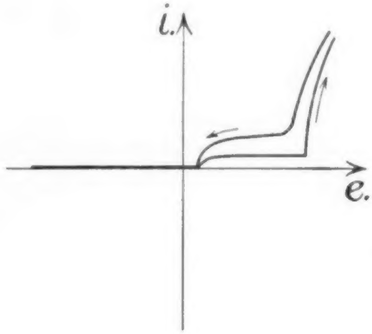

Fig. 4

and the ionization current continued for a brief time, as shown in Figure 3. This ionization current continued for a longer and longer time as the frequency was increased until the figure had the form shown in Figure 4.

The critical frequency was now measured over a range of pressures and arc-lengths. The pressure was varied from 0.15 mm to 10 mm and the arc-length, as measured from the anode to the nearest point of the cathode, was varied from 10 to 30 mm. During these observations the quantity of abnormal atoms present, as measured by the ordinates of the decreasing curve above 4 volts, was kept constant.

Curves plotted from these data are shown in Figure 5. As the pressure increased the critical frequency decreased rapidly to about 70 cycles per second at 2 mm pressure and remained practically constant at 70 cycles per second to 10 mm pressure. The critical frequency increased very slightly as the arc-length decreased from 30 to 10 mm for pressures below 3.5 mm, but was practically independent of these arc lengths for pressures above 3.5 mm and up to 10 mm.

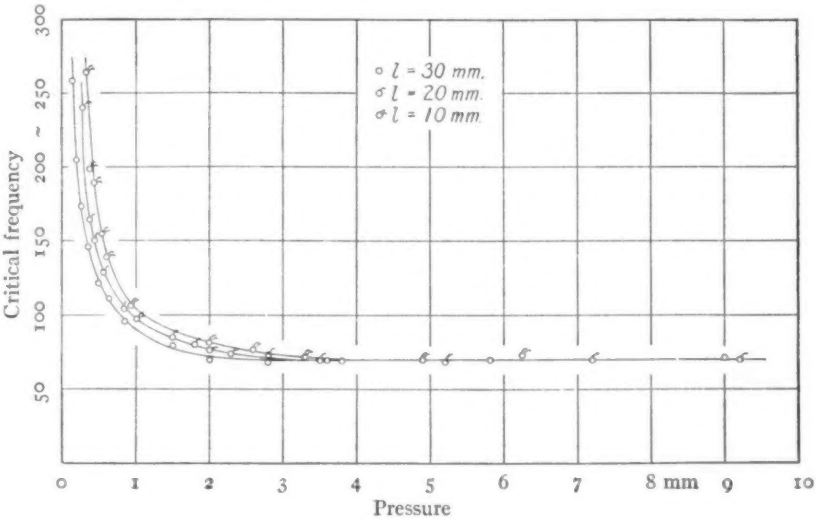

Fig. 5

DISCUSSION

The shape of these curves, as well as the form of the lower ionization current shown in Figure 3, may be interpreted on the concept of a long-lived abnormal helium atom.

In order to produce an observable indication of ionization at about 4 volts, a large number of abnormal atoms must be present when the e.m.f. returns to 4 volts, after having passed through its negative values, otherwise the deflection on the Braun tube screen is too small to be observed. While the e.m.f. is passing through these negative values, the abnormal atoms may escape from the arc space in at least two ways. They may diffuse out from the arc space or they may revert to normal atoms by collision with

impurities. Probably both of these phenomena are going on, for it is very unlikely that the helium was "absolutely" pure.

Diffusion of the atoms out from the arc space would influence the shape of the critical frequency-pressure curve in the following way. At low pressures the abnormal atoms would diffuse rapidly from the arc space, and as the pressure increases this time of diffusion would become longer and longer, finally becoming even greater than the life of an abnormal atom. Since a large number of abnormal atoms are necessary to produce sufficient ionization current to be observable, the e.m.f. must return to 4 volts later and later as the time of diffusion becomes longer and longer; i.e., as the pressure increases the critical frequency becomes smaller. However, when a pressure is reached at which the time of diffusion is comparable with or greater than the life of an abnormal atom, the critical frequency becomes dependent upon the life of the abnormal atom and further increase of the pressure does not lower the critical frequency.

The shape of the critical frequency-pressure curve is in agreement with this idea of diffusion. The constancy of the critical frequency over a large range of pressure (see Figure 5) indicates that the abnormal atom has a definite life of about $\frac{1}{140}$ of a second under the conditions of these experiments. The idea of the handing on of radiation or the imprisonment of radiation suggests a strong dependence on pressure, which is not found to be the case in these experiments.

As pointed out in the introduction, these abnormal atoms are permanently stable in absolutely pure helium, and revert to normal atoms only when conditions exist under which the selection principle is violated. Neglecting the effects at the walls and the electrodes, the life of the abnormal atom would then depend upon the partial pressure of impurities present, for the mean free path between molecules of the impurity would be the controlling factor in determining the life of the abnormal atom. Probably this is the explanation of the longer life obtained in these experiments as compared with that obtained in the earlier experiments, for circulating the gas during observations certainly gave purer helium than was obtained with the gas stagnant in the experimental tube.

The decrease of critical frequency with increasing arc-length is probably due not only to the difference in diffusion times with different arc-lengths, but also to the greater probability of electron impact with longer arc-lengths.

The increase in the time of decay of the lower ionization current as the frequency was gradually increased above the critical frequency is probably due to the persistence of the abnormal atoms; the lower ionization current will continue as long as there are sufficient abnormal atoms present. Manifestly the sooner the e.m.f. returns to 4 volts the longer will the arc continue.

SUMMARY

The experimental results may be summarized as follows:

1. The previously reported measurements of the life of metastable helium atoms were repeated under improved experimental conditions under which a life of approximately $\frac{1}{140}$ of a second was found.

2. Critical frequency-pressure curves have been obtained which show that critical frequency is independent of pressure over a large range of pressure. This fact is interpreted as being caused by a long-lived abnormal atom, rather than being due to the handing on of radiation or the imprisonment of radiation, which suggest a strong dependence on pressure.

3. The departure of the critical frequency-pressure curve from a straight line at low pressures is interpreted on the idea of diffusion of the atoms from the arc space.

4. The observed actual life of about $\frac{1}{140}$ of a second instead of an infinitely long life is supposed to be due to the presence of impurities which cause, at an encounter with an abnormal atom, a violation of the selection principle, bringing the abnormal atom to the normal state.

The author's thanks are due to Mr. Milton Marshall and Miss Ann B. Hepburn for their help in the experimental part of this work, to Dr. H. Rossbacher and Mr. E. E. Rosaire for preparing the filaments, and to Professor A. J. Dempster for many valuable suggestions.

Ryerson Physical Laboratory
January 1924

DETERMINING FACTORS IN THE LIFE OF METASTABLE HELIUM

By A. J. DEMPSTER

ABSTRACT

Mathematical theory of the influence of impurities and diffusion on the apparent life of metastable helium. The experiments of Kannenstine on the life of metastable helium are compared with a theory in which the effects of impurities and diffusion are treated mathematically. If the impurity has a constant partial pressure of 1.8×10^{-5} millimeters of mercury and the diffusion coefficient for the metastable atoms is one-third of that given by the kinetic theory of gases for normal helium, agreement is found on the idea that collisions with the wall cause the metastable state to revert to the normal at once. The dependence of frequency on pressure deduced from a theory of radiation diffusion is found not to agree as well as that based on the idea of a metastable state of the atom which persists until destroyed by a collision with an impurity or with the walls.

In recent experiments with alternating-current arcs it has been shown by Dr. F. M. Kannenstine[1] that the first excited state of the helium atom produced by the impact of 20.45 volts electrons may persist for a considerable time after the excitation is removed. In a later paper he has measured the dependence of the duration of this metastable state on the pressure of the gas. Over a considerable range of pressure the rate of decay is found to be independent of the pressure, but at low pressures the rate apparently increases greatly. He supposes that at the higher pressures the metastable state is destroyed by collision with some impurity that is evolved from the walls or metal parts and is thus present at a constant partial pressure; at low pressures it is to be expected that diffusion would become important and aid in removing the metastable helium from the arc space. In this paper the observed values are compared with those predicted by the kinetic theory of gases.

Kannenstine's experiments were carried out in a spherical vessel of 4 cm radius, and the simplest assumption, that may be handled mathematically, is that the metastable atoms diffuse out to the walls of the vessel, where they give up their energy and revert to normal atoms. If n is the number of metastable atoms per cc and βn the rate of destruction by collisions with the impurity,

[1] *Astrophysical Journal*, **55**, 345, 1922.

we have the following diffusion equation in polar co-ordinates plus the term βn for the change of n with time.

$$\frac{\partial n}{\partial t}=D\left(\frac{\partial^2 n}{\partial r^2}+\frac{2}{r}\frac{\partial n}{\partial r}\right)-\beta n\ .$$

Here D is the diffusion coefficient and r the distance from the center of the sphere. Putting $nr\ e^{\beta t}=w$ the equation reduces to

$$\frac{\partial w}{\partial t}=D\frac{\partial^2 w}{\partial r^2}\ .$$

Since the arc appears to fill the bulb at low pressures where diffusion becomes important, we may assume that initially n is constant and equal to n_0. If we also assume as boundary conditions that $n=o$ for $r=R$, the radius of the sphere, we obtain for the center of the sphere,

$$ne^{\beta t}=2n_0\left(e^{-\frac{\pi^2 Dt}{R^2}}-e^{-\frac{4\pi^2 Dt}{R^2}}+e^{-\frac{9\pi^2 Dt}{R^2}}-\ \ .\ \ .\ \ .\ \ .\right)$$

the problem being similar to the cooling of a sphere having its surface at a fixed temperature.[1]

In Dr. Kannenstine's experiments a frequency f was observed such that during approximately half a cycle $\left(t=\frac{1}{2f}\right)$ the amount of helium in the arc space decayed to a density n_1, so that no striking of an arc in the metastable state could be noticed. If f_0 is the constant frequency at high pressures where diffusion is absent,

$$\frac{n_1}{n_0}=e^{-\frac{\beta}{2f_0}}\qquad \text{and}\ \frac{n_1}{n_0}=2e^{-(\beta+0.617D)\frac{1}{2f}}\ ,$$

the latter equation holding at pressure below 1 mm of mercury where the first term of the series is sufficiently accurate. For these pressures, we may deduce a simple relation between f and p in terms of β, f and D. Putting $f_0=70$, $n_1/n=1/10$, and $D=330/p$ where p is the pressure in millimeters of mercury, we have $\beta=322$ and

$$f=53.8+33.9/p\ .$$

[1] Ingersoll and Zobel, *Theory of Heat Conduction*, p. 133; Weber-Riemann, *Partielle Differential Gleichungen*, **2**, p. 111.

This curve is drawn in Figure 1, and Kannenstine's values for an arc length of 3 cm are indicated as circles. For long arc lengths our initial and boundary conditions are most nearly realized. The values of the curve above one millimeter pressure are computed, using three terms of the series.

We see that the agreement between the observed and computed values is very good for the longest arc length. For shorter arc

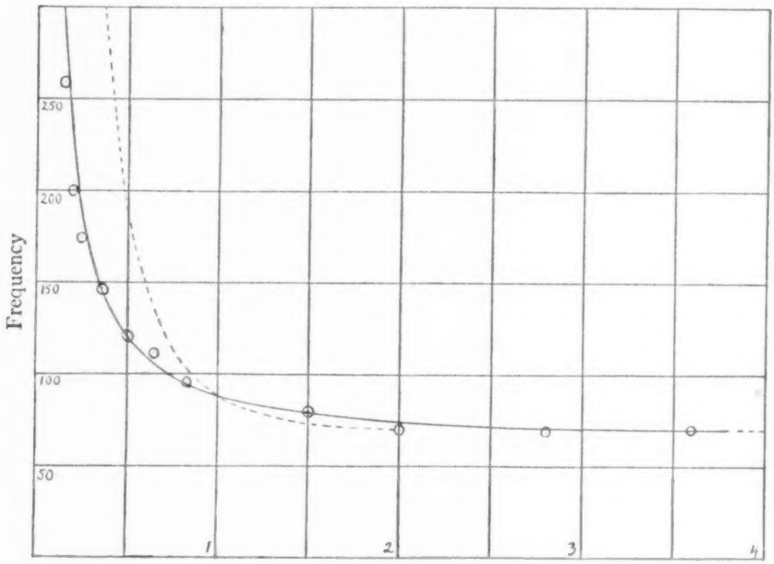

FIG. 1

lengths higher frequencies are observed at the same pressure, possibly due to an increased influence of the electrodes in destroying the metastable helium or, as suggested by Kannenstine, to a restriction of the position for ionization to the neighborhood of the anode.

The value of D given by the kinetic theory of gases is equal to $1.20\ k/\rho$ where k is the coefficient of viscosity and ρ the density, or to $\frac{1}{3}lc$, approximately, where l is the mean free path and c the average velocity. Taking the values for helium as applying to helium in the metastable state, we find $D=1120/p$ where p is the pressure in millimeters of mercury. With our assumption of zero

concentration of the metastable helium at the wall, this coefficient leads to a more rapid decrease than that observed since the agreement in Figure 1 was obtained with a diffusion coefficient $D=330/p$. The models of the helium atom based on Bohr's theory would lead us to expect a smaller free path and a smaller diffusion coefficient for the metastable atom than for the normal. If a reduction to one-third is possible on this ground, we may consider the boundary conditions used above as justified. Otherwise we could modify the boundary conditions by assuming that many collisions must occur at the walls before the metastable state reverts to normal, so that the concentration at the wall is not zero. The problem arising from these assumptions is similar to that of the cooling of a sphere by radiation, and boundary conditions may be found that give agreement with Kannenstine's observations even when the diffusion coefficient for normal helium is used. The solution for the center of the sphere takes the form

$$ne^{\beta t}=c_1e^{-Dm_1^2t}+c_2e^{-Dm_2^2t}+ \quad . \quad . \quad . \quad .$$

where $c_1\, c_2\, m_1\, m_2$ are constants and $m_2 > 2m_1$. Thus for low pressures the first term gives us a relation between f and p of the same type as that found above.

The partial pressure of the impurity that is required to give the rate of decay observed at high pressures may be obtained by equating e^{-322t} to $e^{-x/l}$ or $e^{-\frac{ct}{l}}$ where c is the average velocity of the helium atom and l the average total path before a collision with a molecule of the impurity. This path (373 cm) leads to a partial pressure of the impurity of 1.8×10^{-5} mm of mercury, assuming the molecule to have a radius of 1.9×10^{-8} cm, as would hold for most of the foreign gases that might be present.

In recent papers F. A. Horton and A. C. Davis,[1] and K. T. Compton[2] have claimed that the stability of partially ionized helium may be only apparent, and that the essential phenomenon may be the slow escape of the radiation itself. The time interval during which the atom is in the partially ionized state is assumed

[1] *Philosophical Magazine*, **14**, 1140, 1922.

[2] *Ibid.*, **45**, 750, 1923.

to be of the order of 10^{-7} to 10^{-8} seconds, as required by the classical radiation theory and observed for hydrogen under certain experimental conditions.[1] The radiation is absorbed very rapidly by normal atoms, putting them in turn into the partially ionized state.

As pointed out by Kannenstine, such a view of the decay process involves a strong dependence on the pressure, contrary to the observations at high pressures. It is possible, however, that the diffusion assumed by Kannenstine to occur at low pressures and calculated above on the ideas of the kinetic gas theory may also be interpreted as radiation diffusion in the sense discussed by these authors. A corollary of this interpretation would be that the destruction by impurities at high pressures does not lead to the emission of the radiation of helium corresponding to the return to the normal state, since this radiation would be subject to the slow diffusion process which is found not to apply at these pressures. The excited atoms on this view must be supposed to form temporary compounds and to emit light of other wave-lengths.

Professor K. T. Compton deduces a diffusion coefficient for the radiation $D=\frac{1}{3}\,lc=\frac{1}{3}\;1/\alpha\;\;1/\alpha\tau$. Here l and c, the mean free path and average velocity in the usual kinetic theory formula, are interpreted in terms of α, the absorption coefficient for the radiation, and τ, the average time between successive emissions of the radiation. We thus have $l=1/\alpha$, and the average molecular velocity c is replaced by the average distance that the radiation goes divided by τ. The scattering coefficient given by Lamb, $p/\alpha=1.54/N\lambda^2$, leads to a value $p/\alpha=1.16\times10^{-6}$. This value is multiplied by 10,000 since this correction factor appears necessary for the absorption coefficient of the mercury line $\lambda=2536$. Taking $\tau=2.2\times10^{-7}$ we find the diffusion coefficient $D=203.5/p^2$, where p is the pressure in millimeters of mercury. We see that the coefficient agrees approximately with that used above for values around 1 mm pressure.

An interpretation of the "handing on of radiation" based on a "light-quantum" hypothesis also leads to a diffusion coefficient. If we imagine the radiation to be handed on in concentrated bundles from atom to atom and assume the free path to be of the order of the

[1] W. Wien, *Annalen der Physik*, **60**, 597, 1919; **66**, 230, 1921; A. Dempster, *Physical Review*, **15**, 138, 1920; *Astrophysical Journal*, **57**, 193, 1923.

kinetic theory free path, we have $p/a = 1.6 \times 10^{-5} \times 760 = 1.2 \times 10^{-2}$. Assuming $\tau = 2.2 \times 10^{-7}$ we have $D = \frac{1}{3}\ 1/a\ 1/a\tau = 218/p^2$.

The dependence on pressure is however against these interpretations of the diffusion coefficient. The dotted curve in Figure 1 is the curve obtained by taking $D = 330/p^2$, that is, assuming agreement at 1 mm pressure. We see that the very great diffusion required by the formula at low pressures leads to values of the frequency much greater than those observed. We thus conclude that Kannenstine's observations are in complete agreement with the view that the metastable helium atom produced by electron impacts of 20.4 volts is unable to revert to the normal state except under the influence of collisions with the walls or with some impurity in the helium gas.

Ryerson Physical Laboratory
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SPACE-VELOCITIES OF LONG-PERIOD VARIABLE STARS OF CLASSES Me AND Se[1]

By GUSTAF STRÖMBERG and PAUL W. MERRILL

ABSTRACT

Computation of velocity-ellipsoids.—The three rectangular velocity-components of the motion relative to the sun of 80 long-period variables of spectral classes M and S have been computed from the radial velocities, proper motions, and absolute magnitudes. The stars were divided into two groups according to their spectra: (1) M1e to M6e; (2) M7e, M8e and Se. The elements of the velocity-ellipsoids for each group were determined, and are given in Table I in galactic co-ordinates, and in Table II in equatorial co-ordinates. The direction of the major axis is about the same in both groups as for other classes of stars, but the dispersion of the velocities is much larger, especially for the first group.

The asymmetry in the velocity distribution is very marked among these stars, as evidenced by the fact that the first group (containing the fastest moving stars) is shifted farther from the origin toward the third quadrant of the galactic longitude than is the other group.

Recent determinations of the radial velocities of long-period variable stars[2] in combination with their measured proper motions have enabled us to compute the three components of the space-velocities of 80 variables of spectral types Me and Se. The distances of these stars were obtained from the absolute magnitudes for the different subdivisions as given in a recent investigation.[3] The proper motions were taken from Wilson's list,[4] which includes a few determinations by Miss Young and Miss Farnsworth.

The formulae for computing the three velocity-components in the equatorial system of co-ordinates are given in *Mt. Wilson Contr.*, No. 245.[5] They have been reduced to the galactic system of co-ordinates, the pole of the galaxy being assumed to have the co-ordinates $\alpha = 190\overset{\circ}{.}6$, $\delta = 27\overset{\circ}{.}2$ (1900). The x-axis is directed along the intersection of the galactic plane with the equator (the positive end toward Aquila, right ascension $18^{h}43^{m}$), the y-axis toward 90° galactic longitude, and the z-axis toward the north

[1] *Contributions from the Mount Wilson Observatory*, No. 268.

[2] *Mt. Wilson Contr.*, No. 264; *Astrophysical Journal*, **58**, 215, 1923.

[3] *Mt. Wilson Contr.*, No. 267; *Astrophysical Journal*, **59**, 97, 1924.

[4] *Astronomical Journal*, **34**, 183, 1923.

[5] *Astrophysical Journal*, **56**, 265, 1922.

galactic pole. The equations for computing the galactic co-ordinates (x, y, z) from the equatorial co-ordinates (ξ, η, ζ) are the following:

$$\left.\begin{aligned} x &= +0.185\,\xi - 0.983\,\eta \\ y &= +0.449\,\xi + 0.084\,\eta + 0.889\,\zeta \\ z &= -0.874\,\xi - 0.164\,\eta + 0.457\,\zeta \end{aligned}\right\} \qquad (1)$$

Throughout this investigation the velocities of the stars are referred to the sun as origin and are expressed in kilometers per second.

The fact that the stars studied have fairly large radial velocities makes them of special interest, as they provide additional material for testing the relation between internal speed and group-motion.[1] Evidence that such a relationship exists for these stars was given in a recent investigation of their radial velocities.[2] In that connection it was shown that the solar motion is dependent upon the average residual radial speed of the stars in the group relative to which the sun's motion is referred.

An approximate division into groups of different relative motions could be made simply by grouping the stars according to their spectra. To avoid making the number of stars in each group too small, only two groups were formed. The first contains stars of spectral types M1e to M6e and the second, stars of spectral types M7e, M8e, and Se. These two groups seem from the previous study of the radial velocities to be fairly homogeneous as regards their average velocities.

After the velocity-components relative to the sun and in the galactic system of co-ordinates had been computed, their algebraic means were derived. These means appear in Table I as the co-ordinates of the centers of the two velocity-groups. The moments of second order about the means were then computed from the formulae:

$$\left.\begin{aligned} &\overline{x_1^2} = \overline{(x-\bar{x})^2} = \overline{x^2} - \bar{x}^2 \\ &\overline{x_1 y_1} = \overline{(x-\bar{x})(y-\bar{y})} = \overline{xy} - \bar{x}\,\bar{y} \\ &\text{etc.} \end{aligned}\right\} \qquad (2)$$

[1] *Mt. Wilson Contr.*, No. 245; *Astrophysical Journal*, **56**, 265, 1922.

[2] *Mt. Wilson Contr.*, No. 264; *Astrophysical Journal*, **58**, 215, 1923.

The principal axes were then computed in the ordinary way by introducing the condition that the sums of the squares of the projected velocities should be maxima or minima. Projecting the velocity (x_1, y_1, z_1) upon an axis ξ whose direction-cosines are α_1, α_2, and α_3 we have

$$\xi = \alpha_1 x_1 + \alpha_2 y_1 + \alpha_3 z_1$$

Taking the mean value of the squares of ξ and introducing the additional condition

$$\alpha_1^2 + \alpha_2^2 + \alpha_3^2 = 1$$

we can find the maximum and minimum value of $\overline{\xi^2}$ by equating to zero the partial derivatives of the following expression:

$$\alpha_1^2 \overline{x_1^2} + \alpha_2^2 \overline{y_1^2} + \alpha_3^2 \overline{z_1^2} + 2\alpha_1\alpha_2 \overline{x_1 y_1} + 2\alpha_1\alpha_3 \overline{x_1 z_1} + 2\alpha_2\alpha_3 \overline{y_1 z_1} - \lambda(\alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1)$$

We thus find the following equations:

$$\left.\begin{aligned} \alpha_1(\overline{x_1^2} - \lambda) + \alpha_2 \overline{x_1 y_1} + \alpha_3 \overline{x_1 z_1} &= 0 \\ \alpha_1 \overline{x_1 y_1} + \alpha_2(\overline{y_1^2} - \lambda) + \alpha_3 \overline{y_1 z_1} &= 0 \\ \alpha_1 \overline{x_1 z_1} + \alpha_2 \overline{y_1 z_1} + \alpha_3(\overline{z_1^2} - \lambda) &= 0 \end{aligned}\right\} \qquad (3)$$

These equations give us values of α_1, α_2, and α_3 different from zero, only if the determinant vanishes. This condition leads to the third-degree equation

$$\left.\begin{aligned} &\lambda^3 + p_1\lambda^2 + p_2\lambda + p_3 = 0 \\ &\text{where} \\ &p_1 = -[\overline{x_1^2} + \overline{y_1^2} + \overline{z_1^2}] \\ &p_2 = \overline{x_1^2}\,\overline{y_1^2} + \overline{x_1^2}\,\overline{z_1^2} + \overline{y_1^2}\,\overline{z_1^2} - \overline{x_1 y_1}^2 - \overline{x_1 z_1}^2 - \overline{y_1 z_1}^2 \\ &p_3 = -\overline{x_1^2}\,\overline{y_1^2}\,\overline{z_1^2} - 2\overline{x_1 y_1}\,\overline{x_1 z_1}\,\overline{y_1 z_1} + \overline{x_1^2}\,\overline{y_1 z_1}^2 + \overline{y_1^2}\,\overline{x_1 z_1}^2 + \overline{z_1^2}\,\overline{x_1 y_1}^2 \end{aligned}\right\} \qquad (4)$$

After solving the cubic equation, we can find the three direction-cosines of each of the three principal axes from equation (3). The dispersions (mean square velocities) along the three principal axes are equal to the square-roots of the three values of λ.

The galactic longitudes and latitudes of the three principal axes, together with the dispersion along each axis (a, b, c), are found in Table I.

This method of computing the velocity-ellipsoids, which has been used by Newcomb (for other purposes), Charlier, Raymond, Gyllenberg, and others, is probably the simplest one, but has the disadvantage of giving altogether too high weights to large velocities. It is analogous to the computation of mean errors from the sums of the squares of the residuals. If the observations are few in number and have a large dispersion, and especially if the distribution of errors (velocities) does not follow closely the assumed

TABLE I

ELEMENTS OF THE TWO VELOCITY-ELLIPSOIDS REFERRED TO THE SUN AND TO THE GALACTIC SYSTEM OF CO-ORDINATES

Spectrum	No. Stars	Center			Major Axis			Intermediate Axis			Minor Axis		
		x	y	z	L	B	a	L	B	b	L	B	C
		km/sec.	km/sec.	km/sec.			km/sec.			km/sec.			km/sec.
M1e to M6e..	47	−35.3	−20.8	−5.1	164°1	−2°1	55.0	232°	+84°5	46.4	74°3	+ 5°1	38.4
M7e, M8e, Se.	30	−20.8	−13.9	−1.4	161.0	−8.0	37.8	69.9	− 7.2	24.2	118	+79.2	20.5

TABLE II

ELEMENTS OF THE VELOCITY-ELLIPSOIDS REFERRED TO THE EQUATORIAL SYSTEM OF CO-ORDINATES. DISPERSION ALONG PRINCIPAL AXES CORRECTED FOR THE EFFECT OF ACCIDENTAL ERRORS IN THE ABSOLUTE MAGNITUDES AND THE PROPER MOTIONS

Spectrum	Center			Major Axis			Intermediate Axis			Minor Axis		
	α	δ	v	α	δ	a	α	δ	b	α	δ	c
			km/sec.			km/sec.			km/sec.			km/sec.
M1e to M6e...	108°7	−30°3	41.3	91°3	+13°1	49.8	186°9	+22°8	40.2	333°6	+63°2	31.0
M7e, M8e, Se..	114.4	−31.2	25.1	84.5	+12.9	35.7	338.2	+50.4	21.1	184.2	+36.6	17.1

distribution-law, the dispersion computed from the sum of the squares may be misleading. If the number of stars is large enough, the method devised in *Contribution* No. 245, with proper weights attached to the equations of condition, probably gives better results. The application of this method is hardly warranted in the present case as the number of stars is too small.

The dispersions a, b, c given in Table I are systematically affected by the accidental errors in the proper motions and parallaxes. These errors produce a dispersion in addition to that due to the true velocities. If we assume the mean errors in the absolute

magnitudes to be ±0.4 and accept the errors given by Wilson in his list of proper motions (*loc. cit.*) we can correct the dispersion for the effect of these errors. These corrected values of the dispersion are given in Table II together with the equatorial co-ordinates of the centers and of the principal axes.

The data given in Tables I and II show that the major axes of the two groups are nearly parallel to each other. The minor axis

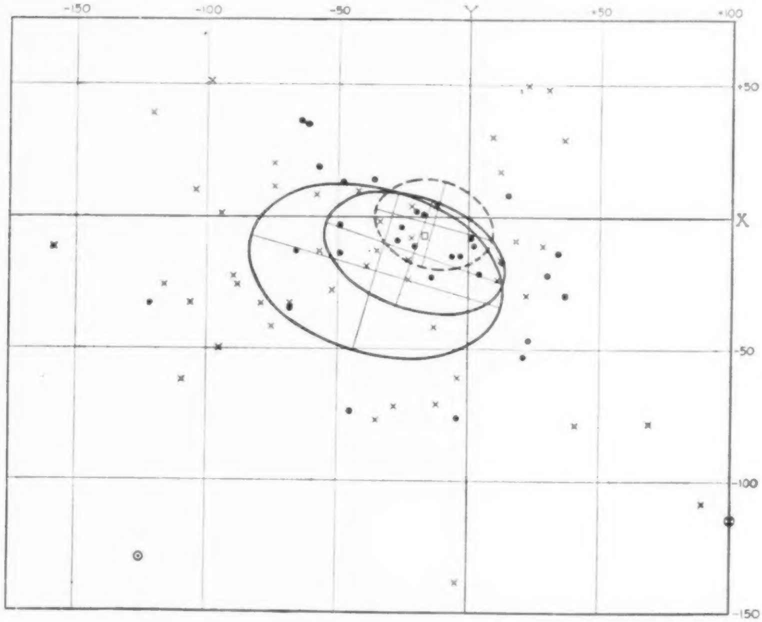

FIG. 1.—Projection of the velocity-ellipsoids on the galactic plane. The largest ellipse corresponds to stars of classes M1e to M6e (represented by crosses). The other solid-line ellipse corresponds to stars of classes M7e, M8e, and Se (represented by dots). Points inclosed in small circles were omitted in the computations. The dotted ellipse corresponds to slow-moving stars of other spectral types.

for the first group falls near the galactic plane, whereas the minor axis for the second group passes near the galactic pole. Whether this difference is real or not, it is impossible to say because the two smaller axes for the second group are nearly equal. Wilson found in his study of the proper motions of 219 red stars that the smallest axis is directed toward the pole of the galaxy, but the dispersions

along the two smaller axes do not differ much. The directions of the major axes are in fair agreement with the values given by Wilson, $\alpha = 98^\circ.0$, $\delta = +11^\circ.9$.

The most interesting feature is the difference in group-motion as evidenced by the different co-ordinates of the centers of the two groups. This shift of the center of the velocity group with increasing internal motion is very striking for this class of stars. In our previous paper[1] a close correlation was found between the solar

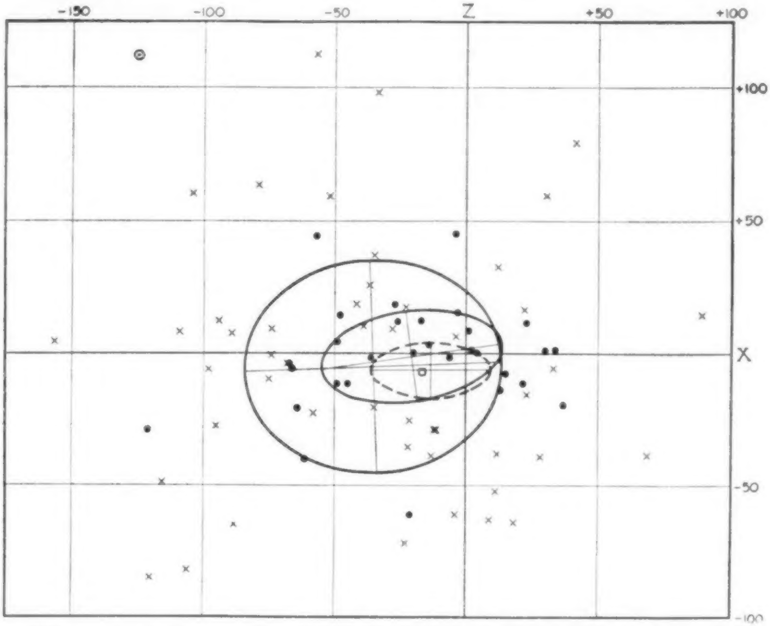

FIG. 2.—Projection of the velocity-ellipsoids on a plane perpendicular to that of the galaxy.

velocity and the average radial velocity for the different subdivisions of spectral type Me. This shift is really an indication of an inherent asymmetry in the velocity-distribution, which seems to be of a very general nature as it can be traced among all classes of stars and even among globular clusters and spiral nebulae.[2]

In the diagrams are shown the projections of the two velocity-ellipsoids on the xy- (galactic) and xz-planes. The crosses and dots

[1] *Mt. Wilson Contr.*, No. 267; *Astrophysical Journal*, **59**, 97, 1924.

[2] *Proceedings of the National Academy of Sciences*, **9**, 312, 1923.

represent the velocities for individual stars in the first and second groups, respectively, projected on the two planes. The line from the origin to a cross or dot thus represents the velocity-vector of a star relative to the sun, projected on these two planes. The dotted ellipse is the intersection with the two planes of the velocity-ellipsoid for stars of small relative velocity, the elements of the velocity-ellipsoid being taken from the data given in *Mount Wilson Communications*, No. 84.[1] The small square indicates the general group-motion of ordinary stars and has the co-ordinates -17.0, -7.4, -7.4 km. The vector from the small square to the origin represents the usually adopted velocity of the sun relative to the stars. In equatorial co-ordinates this velocity is 20 km/sec. toward the apex $\alpha = 270°$, $\delta = +30°$. The small square does not coincide with the center of the smallest ellipsoid because the velocity of the sun as derived from stars of small velocity is itself somewhat smaller than the velocity derived from bright stars in general.

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[1] *Proceedings of the National Academy of Sciences*, **9**, 312, 1923.

THE ELECTRIC FURNACE SPECTRUM OF TITANIUM IN THE ULTRA-VIOLET[1]

By ARTHUR S. KING

ABSTRACT

Furnace spectrum of titanium, λ 2600 to λ 3883.—This paper supplements *Mount Wilson Contribution*, No. 76, published in 1914, which covered the region λ 3888 to λ 7364. Temperature stages of 2000°, 2250°, and 2600°C. were employed to observe the initial appearance and rate of increase in intensity of the ultra-violet lines. The spectrograms were made in the first and second orders of a 15-foot concave grating. The table gives the temperature classification of 785 lines, and their relative intensities in the arc and at the three furnace temperatures. New wave-lengths are given for 333 furnace lines which have not been measured in the arc spectrum, or for which the arc values are poor, owing to diffuseness or blends. Many of the new wave-lengths are for lines which are very weak in the arc, denoted by I A, II A, etc. Comparison photographs of the spark spectrum were made for the selection of enhanced lines, which in this region are found to appear at lower temperature than the enhanced lines in the visible spectrum. The classification thus includes many lines of the ionized atom, and note is made of phenomena of reversal and dissymmetry in the condensed spark. A mixture of titanium with potassium had the effect of suppressing the enhanced lines of titanium, as has been noted in other cases of mixture with elements of lower ionizing potential.

A former paper[2] by the writer gave the furnace lines of titanium in the visible spectrum, with their classification. The material now presented covers the ultra-violet as far as λ 2600. In this region, the enhanced lines are very numerous, and a large proportion of them are emitted at the higher furnace temperatures. It has been possible, therefore, not only to classify the lines of the neutral atom with fair completeness, but to make a beginning for the ionized spectrum by including the stronger enhanced lines, with their furnace intensities and their behavior as to reversal and dissymmetry in the spark.

As the wave-length tables for this region are far from complete, and as the vacuum furnace emits strongly many lines which are faint in the arc, and sharpens others which in the arc are wide and hazy, it has been necessary to measure a large part of the furnace spectrum. This has resulted in the listing of many new lines, and in the revision of some arc wave-lengths which are notably poor. Of the 785 lines tabulated, new wave-length values are given for 333.

[1] *Contributions from the Mount Wilson Observatory*, No. 274.

[2] *Mt. Wilson Contr.*, No. 76; *Astrophysical Journal*, **39**, 139, 1914.

The electric furnace employed was the later type of tube resistance-furnace,[1] operated in vacuum. Either titanium carbide or a c.p. metallic powder was used. Both preparations entered into combination with the graphite tube, and stayed in place, thus providing an abundant supply of vapor during the run. The use of absorption spectra in the region of short wave-lengths, produced by passing the light from a tungsten lamp or from wire explosions through the furnace, was effective in bringing out only some of the easily reversible lines, the bulk of the lines in this region being either enhanced or high-temperature furnace lines.

Temperature stages which gave decided differences in the spectrum were approximately 2000°, 2250°, and 2600° C. These are designated as low, medium, and high, respectively.

The spectrograms as far as λ 2700 were made in the second order of a 15-foot concave grating, the scale being 1.86 A per millimeter. A few lines of shorter wave-length were obtained by using the first order of this grating and of a 1-meter concave grating.

EXPLANATION OF THE TABLE

Wave-lengths.—International wave-lengths to two decimal places are given in the first column. In the second column, lines measured by the writer are left without initial. For the most part, these are lines faint in the arc, but distinct and often strong in the furnace. In addition, improved values are given for many diffuse arc lines, some of which are so hazy in the arc that no previous measurement has been attempted. The sharpening action of the vacuum furnace permits good measurements in such cases, and also for some close pairs which have not previously been resolved. Of the other wave-lengths, those marked "K" are due to Kilby,[2] "E" to Exner and Haschek,[3] "H" to Hasselberg,[4] "R" to Rowland,[5] the last three being reduced to the international system. An asterisk following the wave-length refers to a note at the end of the table.

[1] *Mt. Wilson Contr.*, No. 247; *Astrophysical Journal*, **56**, 318, 1922.

[2] *Astrophysical Journal*, **30**, 243, 1909.

[3] *Spektren der Elemente bei normalem Druck*, Leipzig, 1911.

[4] *Astrophysical Journal*, **4**, 116, 212, 1896.

[5] *Preliminary Table of the Solar Spectrum Wave-lengths.*

Arc and furnace intensities.—Columns 3 to 6 give the intensities for the arc and for three furnace temperatures. A line distinctly outlined in the negative is given the intensity "1," a fainter appearance being indicated as "trace" ("tr"); "n" and "N" denote degrees of diffuseness in the structure of arc lines, while "r" and "R" indicate partial and complete self-reversal, respectively. The extreme diffuseness of some arc lines precludes any estimate of their intensities, and certain portions of the furnace spectrum are disturbed by the cyanogen bands at the higher temperatures. The intensities are questioned in such cases, and a note of explanation is usually given at the end of the table.

Classes.—The final column gives the classes assigned according to the usual method. Classes I and II appear at low temperature, the lines of class I being relatively strong, and often show little increase at higher temperatures. Lines of class II change more rapidly, and are among the most prominent in the arc. Lines of class III are usually well developed at medium temperature, while lines belonging distinctly to high temperature are placed in class IV. Titanium lines of class V are almost always enhanced lines, since the high-temperature furnace is capable, for this element, of giving practically the whole spectrum of the neutral atom, except in the region of wave-length so short that the furnace ceases to emit.

The letter "A" after the class number designates lines relatively stronger in the furnace than in the arc. "E" following the class number indicates an enhanced line. If the enhanced line reverses in the condensed spark, this is denoted by "Er," while "u" is added if the reversal is unsymmetrical.

TABLE I

TEMPERATURE CLASSIFICATION OF TITANIUM LINES

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
2599.93*....	E	15	2	....	....	IV
2605.16*....	E	15	2	....	....	IV
2611.30*....	E	15	2	....	....	IV
2619.96*....	E	12	1	....	....	IV
2641.10*....	E	30	10	?	2	II
2644.25*....	E	30	10	?	2	II
2646.61*....	E	35	10	?	2	II
2657.17*....	E	4	2	....	....	IV
2661.98*....	E	10	1	....	....	IV
2669.60*....	E	12	1	....	....	IV
2679.94*....	E	15	1	....	....	IV
2725.04.....	E	10	5	2	....	III
2727.38.....	E	8	5	2	....	III
2731.58.....	E	6	5	1	....	III
2733.27.....	E	15	5	4	....	III
2735.29.....	E	8	4	2	....	III
2735.61.....	E	8	10	4	....	III
2739.78.....	E	10	6	3	....	III
2742.30.....	E	15	6	5	....	III
2749.04.....	E	5	4	2	....	III
2750.15.....	E	2	1	1	....	III
2757.40.....	E	6	4	1	....	III
2758.06.....	E	10	6	2	....	III
2764.83.....	K	1	....	....	....	V E
2802.47.....	K	15	10	6	....	III
2805.68.....	K	6	8	2	....	III
2806.41.....	K	1	....	....	....	V E
2809.15.....	K	5	8	2	....	III
2810.28.....	K	1	....	....	....	V E
2812.96.....	K	2	6	1	....	IV A
2817.84.....	K	2	5	tr	....	IV A
2820.25.....	K	1	....	....	....	V E
2821.51.....	....	1	3	....	....	IV A
2822.03.....	....	tr	2	....	....	IV A
2823.46.....	....	1	3	....	....	IV A
2825.06.....	....	1	2	....	....	IV A
2825.38.....	K	2n	6	1	....	IV A
2826.37.....	....	tr	1	....	....	IV A
2828.05.....	K	2	6	1	....	IV A
2828.15.....	....		....	....	....	V E
2830.03.....	....	2n	4	....	....	IV A
2831.06.....	....	tr	1	....	....	IV A
2831.40.....	....	1n	3	....	....	IV A
2832.16.....	K	5	....	....	....	V E
2832.26.....	....	1n	2	....	....	IV A
2834.75.....	....	2	6	....	....	IV A
2835.63.....	....	2	2	....	....	IV
2836.09.....	....	1	3	....	....	IV A
2836.40.....	....	1n	3	....	....	IV A
2836.60.....	....	1	3	....	....	IV A

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
2841.91	K	7	1	....	....	V Er
2849.16	....	1	3	....	....	IV A
2851.09	K	2	....	....	....	V E
2853.43	....	1	5	1	....	IV A
2853.92	K	2	....	....	....	V E
2855.13	....	1	1	....	....	IV
2855.22	....	1	5	1	....	IV A
2858.40	K	1	....	....	....	V E
2859.97	....	1	6	2	....	IV A
2860.27	....	2	4	....	....	IV A
2861.29	K	1	....	....	....	V E
2862.31	K	4	....	....	....	V E
2868.73	K	2	....	....	....	V E
2877.42	K	6	....	....	....	V E
2881.94	....	1	2	....	....	IV A
2883.23	....	1	2	....	....	IV A
2884.10	K	7	....	....	....	V E
2886.04	K	2	4	....	....	IV A
2887.46	K	1	....	....	....	V E
2888.92	K	2	....	....	....	V E
2891.05	K	3	....	....	....	V E
2891.63	....	1	1	....	....	IV
2896.75	....	1	1	....	....	IV
2896.89*	....	?N	3	....	....	IV
2901.04*	....	?N	4	....	....	IV
2902.19*	....	?N	2	....	....	IV
2903.17	....	2	3	....	....	IV
2905.65	K	5	10	2	....	IV A
2909.91	K	1	....	....	....	V E
2912.07	K	40	15	15	2	III
2912.47	....	2	5	....	....	IV A
2922.92	....	2	10	1	....	IV A
2923.62*	....	1	12	6	....	III A
2924.01	K	2	....	....	....	V E
2928.32	K	30	15	10	....	III
2933.53	K	25	30r	12	4	II
2937.30	K	25	30r	12	4	II
2941.99*	K	60r	100R	25r	6	II
2947.72	....	3	10	6	....	III A
2948.25*	K	60r	100R	25r	6	II
2956.13*	K	70R	125R	30r	8	II
2956.80	K	25	25r	15	5	II
2959.28	....	tr	1	....	....	IV A
2959.71	....	3	10	3	....	III A
2959.98	....	5	10	5	....	III A
2961.48	....	2	6	1	....	III A
2965.68	K	8	8	3	....	III
2965.72	....	15	10	6	....	III
2966.38	....	1	2	....	....	IV
2967.22	K	25	25r	12	5	II
2967.42	....	tr	1	....	....	IV A
2968.23	K	4	15	8	....	III A

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities: High Temp.	Med. Temp.	Low Temp.	Class
2969.07*	....	1N	1	....	....	IV
2969.37*	....	1	4	1	....	IV A
2970.38	K	10	20r	10	4	II A
2970.55	K	4	10	2	....	III A
2971.50	....	2n	2	....	....	IV
2974.93	K	4	10	3	....	III A
2976.32	....	2	6	2	....	III A
2980.28	....	tr	2	....	....	IV A
2980.76	....	tr	1	....	....	IV A
2982.90	....	tr	1	....	....	IV A
2983.29	K	20	15	12	5	II
2983.39	....	tr	1	....	....	IV A
2985.46	....	3	12	8	tr	III A
2985.98	....	tr	1	....	....	IV A
2986.87	....	tr	1	....	....	IV A
2988.64	....	1	2	....	....	IV A
2989.28	....	1n	1	....	....	IV
2989.42	....	tr	1	....	....	IV A
2989.91	....	tr	1	....	....	IV A
2990.03	....	3	6	1	....	IV A
2990.48	....	3	6	1	....	IV A
2990.98	....	3	6	1	....	IV A
2991.40	....	2N	2	....	....	IV
2991.79	....	1	4	tr	....	IV A
2993.05	....	tr	1	....	....	IV A
2993.94	....	tr	1	....	....	IV A
2995.75	....	4	5	....	....	IV
2996.58	....	2	2	....	....	IV
2998.41	....	tr	1	....	....	IV A
2999.18	....	2n	2	....	....	IV
2999.78	....	tr	1	....	....	IV A
3000.25	....	1n	1	....	....	IV
3000.87*	K	20	15?	12	5	II
3001.88	....	1	3	....	....	IV A
3002.73	K	3	12	10	....	III A
3003.65	....	2n	4	....	....	IV A
3005.07	....	tr	tr	....	....	IV
3005.37	....	2n	4	....	....	IV A
3007.48	....	4N	4	....	....	IV
3010.12	....	tr	2	....	....	IV A
3012.63	....	tr	1	....	....	IV A
3012.99	....	2n	2	....	....	IV
3013.73	....	1	1	....	....	IV
3014.77	....	1	1	....	....	IV
3014.93	....	2	2	....	....	IV
3015.21	....	1	1	....	....	IV
3015.38	....	tr	1	....	....	IV A
3015.55	....	4n	3	....	....	IV
3017.18	K	4	....	....	....	V Eru
3018.52	....	1	1	....	....	IV
3021.56	....	3	4	1	....	IV
3022.48	....	1n	1	....	....	IV

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3024.36	....	1	1	....	....	IV
3024.59	....	2n	2	....	....	IV
3025.06	....	2	8	3	....	III
3029.72	K	4	....	....	....	V E
3031.03	....	1	6	2	....	III A
3038.64	....	1n	1	....	....	IV
3042.54	K	3	12	12	1	III A
3043.85	K	1	....	....	....	V E
3046.67	K	5	....	....	....	V E
3048.77	K	1	....	....	....	V E
3056.74	K	4	....	....	....	V E
3058.08	K	7	....	....	....	V Eru
3059.73	K	5	1	....	....	IV
3063.48	K	2	....	....	....	V E
3065.26	....	1n	1	....	....	IV
3066.20	K	30	8	1	....	IV Er
3066.36*	K	20	?	?	....	IV Er
3066.52*	K	3	?	?	....	IV Er
3068.42	....	1n	1	....	....	IV
3071.23	K	4	....	....	....	V E
3072.10	K	30	8	2	....	III Er
3072.97	K	40	10	4	....	III Er
3075.22	K	40	10	5	....	III Er
3078.64	K	45	12	8	....	III Er
3079.82	....	1	4	1	....	III A
3080.17	K	1	1	tr	....	III
3082.62	....	2	6	2	....	III A
3084.81	K	4	8	4	....	III A
3085.03	....	2n	2	....	....	IV
3085.96	....	1n	tr	....	....	IV
3086.82	....	1	3	....	....	IV A
3088.03	K	60	15	10	tr	III Er
3089.39	K	6	....	....	....	V Er
3090.13	K	8	12	6	....	III
3093.83	....	3n	3	....	....	IV
3097.18	K	7	....	....	....	V Er
3100.07	....	tr	1	....	....	IV A
3100.67*	....	12	25	15	3	III A
3101.48	....	4n	4	1	....	III
3101.77	....	1n	2	....	....	IV A
3102.50	....	3n	4	1	....	III
3103.80	K	6	tr	....	....	V Er
3105.08	K	5	....	....	....	V Er
3105.22	....	2n	2	tr	....	IV
3106.23	K	10	1	....	....	V Er
3106.80	K	8	20	8	....	III A
3107.45	K	12n	6	1	....	IV
3109.58	K	8n	5	1	....	IV
3110.61*	....	4	5	1	....	IV
3111.28	K	10n	5	1	....	IV
3112.05	K	3	....	....	....	V E
3112.48	K	8	10	6	....	III

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3114.09	K	20n	8	2	....	IV
3117.45	K	6	10	4	....	III
3117.66	K	8	1	....	....	V E
3117.89	....	5	10	4	....	III A
3118.13	K	15	8	2	....	IV
3119.41	....	1	1	....	....	IV
3119.73	....	15	12	10	2	III
3119.80	E	5	....	....	....	V E
3119.97	....	2	2	....	....	IV
3120.21	....	3	2	....	....	IV
3121.60	K	2	....	....	....	V E
3122.80	....	tr	2	....	....	IV A
3123.07	K	15	12	10	5	II
3123.76	K	20n	10	2	....	IV
3124.74	....	1	3	tr	....	IV A
3125.16	....	2	6	1	....	IV A
3125.55	....	2	3	tr	....	IV
3127.23	....	2	3	tr	....	IV
3127.43*	....	?	2	....	....	IV A
3127.67	....	8N	3	tr	....	IV
3127.90	....	5	3	....	....	IV
3128.64	K	8	8	1	....	IV
3129.07	K	7	8	1	....	IV
3129.62	....	1	2	....	....	IV A
3130.16	....	8N	5	1	....	IV
3130.38	....	1	2	....	....	IV A
3130.81*	....	15?	10?	1	....	IV
3132.1	....	3N	1	....	....	IV
3132.71	....	6N	3	tr	....	IV
3133.13	....	1	2	....	....	IV A
3134.66	....	1	2	....	....	IV A
3135.05	....	8N	6	1	....	IV
3136.03	E	2	2	tr	....	IV
3138.62	....	1n	4	1	....	IV A
3139.87	....	10N	6	1	....	IV
3141.51	K	15	12	10	4	II
3141.67	K	10	8	1	....	IV
3143.34	....	12N	8	2	....	IV
3143.75	K	10	4	1	....	IV E
3144.72	K	2	....	....	....	V E
3145.51	....	1	5	2	....	IV A
3146.24	....	3N	5	1	....	IV
3147.26	K	3	6	1	....	IV A
3147.42	....	1	3	tr	....	IV A
3148.03	K	12	5	1	....	IV E
3151.11	....	tr	2	tr	....	IV A
3152.24	K	12	5	1	....	IV Eru
3153.59	K	3	10	3	....	III A
3154.18	K	10	5	1	....	IV Eru
3155.65	K	10	5	1	....	IV Eru
3157.39	K	2	tr	....	....	IV
3157.66	....	1	10	5	....	III A

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3160.09	....	tr	3	1	....	III A
3161.19	K	20	7	2	....	III Eru
3161.76	K	20	8	3	....	III Eru
3162.56	K	25	10	3	....	III Eru
3163.92	....	1	1	....	....	IV
3168.04	....	2n	2	tr	....	IV
3168.52	K	30	12	4	....	III Eru
3170.92	K	3	12	8	2	III A
3172.38	....	1n	1	....	....	IV
3172.72	K	4	12	4	....	III A
3179.28	K	3	6	3	....	III A
3179.59	....	1n	2	1	....	III A
3180.8	....	1	1	....	....	IV
3181.4	....	1n	1	....	....	IV
3181.9	....	1n	1	....	....	IV
3182.3	....	1n	1	....	....	IV
3186.45	K	60r	60R	30r	15	II
3187.79	....	tr	1	....	....	IV A
3188.48	....	2	1	....	....	IV
3190.87	K	20	3	tr	....	IV Er
3192.00	K	80R	80R	40r	20	II
3193.16	....	tr	1	....	....	IV A
3195.71	K	2	....	....	....	V E
3197.51	K	4	1	....	....	IV E
3198.71	....	1n	2	tr	....	IV A
3199.43	....	1n	2	tr	....	IV A
3199.91	K	100R	100R	50r	25	II
3201.59	K	5	8	4	....	III
3202.52	K	12	1	....	....	V Er
3203.42	K	4	1	....	....	IV
3203.58	....	....	2	1	....	III A
3203.82	K	15	20r	12	12	I
3204.87	K	6	8	5	tr	III
3205.15	....	2	8	6	1	III A
3205.85	K	5	8	8	3	II
3206.34	K	5	4	1	....	IV
3206.82	K	5	4	1	....	IV
3207.33	K	5	6	3	1	III
3207.90	K	5	4	1	....	IV
3209.02	K	4	4	1	....	IV
3209.83	....	2	3	tr	....	IV
3209.94	....	1	2	....	....	IV A
3210.63	....	1	1	....	....	IV
3211.07	....	1n	1	....	....	IV
3213.14	K	8	12	6	1	III
3213.39	....	tr	1	....	....	IV A
3213.81	....	tr	1	....	....	IV A
3214.23	K	12	20r	12	12	I
3214.76	K	6	2	tr	....	IV E
3216.19	....	3	6	3	....	III A
3217.04	K	15	6	3	....	III Er
3217.95	K	8	6	3	....	III

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3218.25	K	8	2	tr	....	IV Eru
3218.67	....	tr	1	....	....	IV A
3218.98	....	2N	2	1	....	III
3219.21	K	8	6	3	....	III
3219.33*	....	1n?	2	1	....	III
3220.28	....	1	3	1	....	III A
3221.14	....	2	8	6	1	III A
3221.37	K	10	8	3	....	III
3222.54	....	1	2	1	....	III A
3222.74	....	3	10	10	4	II A
3222.82	K	15	8	4	....	III Er
3223.00	....	2N	3	1	....	III
3223.51	....	10	8	4	....	III
3223.87	....	1	2	....	....	IV A
3224.23	K	8	tr	....	....	V Eru
3226.11	K	12	10	4	....	III
3226.22	....	1	10	6	1	III A
3226.49	....	1N	1	tr	....	IV
3226.76	K	5	1	....	....	IV E
3227.94	....	2N	2	1	....	III
3228.17	....	2	3	1	....	III
3228.59	K	10	1	....	....	V Er
3229.18	K	15	8	3	....	III Er
3229.40	K	10	1	....	....	V Eru
3229.86	....	tr	1	....	....	IV A
3231.30	K	6	2	1	....	III E
3232.26	K	8	1	tr	....	IV Eru
3232.78	....	3	4	1	....	IV
3234.52	K	60	15	8	2	III Er
3236.10	K	8	tr	....	....	V Er
3236.21	....	tr	2	1	....	III A
3236.57	K	50	15	8	2	III Er
3238.20	K	4	4	1	....	IV
3239.03	K	40	12	7	1	III Er
3239.65	K	8	1	....	....	V Er
3241.97	K	40	12	7	1	III Er
3243.51	....	3	3	1	....	III
3243.80	....	4	15	12	3	III A
3248.60	K	15	5	2	....	III Er
3249.37	K	2	....	....	....	V E
3249.57	....	....	2	1	....	III A
3251.89	K	20	8	3	....	III Er
3252.85	K	25	8	4	....	III Er
3254.23	K	20	8	3	....	III Er
3258.26	....	2n	2	tr	....	IV
3259.04	....	1	2	tr	....	IV A
3259.41	....	2	2	tr	....	IV
3260.26*	K	3	5	2	....	III E
3260.39	....	1	1	....	....	IV
3261.59	K	25	1	....	....	V Er
3262.63	....	1	2	tr	....	IV A
3263.68	K	2	....	....	....	V E

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3263.83	....	2n	2	1	....	III
3265.46	....	2	5	2	....	III A
3267.06	....	2n	3	1	....	III
3267.41	....	tr	1	....	....	IV A
3268.60	....	1	4	2	....	III A
3270.56	K	3	7	2	....	III A
3271.63*	K	10	?	?	....	V Er
3272.06	K	10	tr	....	....	V Er
3275.28	K	2	....	....	....	V E
3276.76	K	4	tr	....	....	V E
3277.93	....	1	1	....	....	IV
3278.28	K	10	tr	....	....	V Er
3278.91	K	15	1	....	....	V Er
3278.96*	....	?	12	8	tr	III A
3279.98	K	3	....	....	....	V E
3280.38	....	2	4	2	....	III A
3282.32	K	8	1	....	....	V Er
3283.94	....	2	2	tr	....	IV
3285.04	....	1	1	....	....	IV
3285.24	....	2	2	tr	....	IV
3287.64	K	10	tr	....	....	V Er
3288.13	K	3	1	....	....	IV
3288.42	K	2	....	....	....	V E
3288.58	K	3	1	....	....	IV E
3292.06	K	20	15	15	10	I
3294.89	K	6	4	1	....	IV
3295.64	....	1	2	tr	....	IV A
3296.36	....	2	2	tr	....	IV
3296.9	....	tr	tr	....	....	IV
3297.08	....	1	1	tr	....	IV
3297.24	....	1	1	tr	....	IV
3297.78	....	1	1	tr	....	IV
3299.41	....	10	12	10	3	III
3301.6	....	1	tr	....	....	IV
3302.09	K	2	....	....	....	V E
3302.36	....	tr	1	....	....	IV A
3303.58	....	1n	1	....	....	IV
3303.85	....	1N	tr	....	....	IV
3305.29	....	2	2	....	....	IV
3305.75	....	2	1	....	....	IV
3306.87	K	10	6	3	....	III
3307.95	....	1n	1	....	....	IV
3308.38	K	10	12	10	3	III
3308.79	K	8	3	1	....	III Eru
3309.49	E	15	15	12	8	I
3309.71	K	6	5	2	....	III
3310.08	....	1n	tr	....	....	IV
3310.39	....	2n	1	....	....	IV
3311.20	....	1n	tr	....	....	IV
3312.68	K	5	4	2	....	III
3314.42	....	10	10	10	10	I
3314.50	....	8	8	8	2	III

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3315.22	...	2	5	1	...	IV
3315.32	K	4	...	...	...	V E
3315.78	...	2n	1	...	...	IV
3316.38	...	1	1	...	...	IV
3317.40	...	1n	1	...	...	IV
3318.01	K	8	3	1	...	III Eru
3318.35	K	4	4	1	...	IV
3318.76	...	1	1	tr	...	IV
3320.16	...	2n	1	...	...	IV
3321.27	...	1n	tr	...	...	IV
3321.58	K	8	10	10	3	III
3321.70	K	6	...	...	...	IV Er
3322.93	K	20	8	5	1	III Eru
3323.66	...	2n	3	tr	...	IV
3323.80	...	4	3	1	...	III
3323.89	...	2	4	1	...	IV A
3324.61	...	1	3	1	...	III A
3324.74	...	4	3	1	...	III
3325.15	...	3	2	tr	...	IV
3325.22	...	3	2	tr	...	IV
3325.37	...	1n	1	tr	...	IV
3326.64	...	2	5	3	...	III A
3326.76	K	5	2	1	...	III Eru
3327.3	...	1n	tr	...	...	IV
3328.34	...	1	tr	...	...	IV
3328.6	...	1n	tr	...	...	IV
3329.45	K	20	8	4	tr	III Eru
3329.82	...	tr	1	...	...	IV A
3332.10	K	8	1	...	...	V Er
3333.02	...	2n	1	tr	...	IV
3333.91	...	2	8	7	1	III A
3334.05	...	1	tr	...	...	IV
3334.88	...	1	1	...	...	IV
3335.19	K	20	8	4	...	III Eru
3336.12	...	1n	1	...	...	IV
3336.58	...	1n	1	...	...	IV
3336.94	...	1	2	tr	...	IV A
3337.40	...	1n	tr	...	...	IV
3337.79	E	2	...	...	...	V E
3338.82	...	2	5	2	...	III A
3339.5	...	1n	1	...	...	IV
3340.33	K	15	7	2	...	III Eru
3341.54	...	1	4	2	...	III A
3341.87*	K	50r	50R	40r	20	II
3342.14	K	6	15r	15	12	I A
3342.70	K	2	10	10	3	II A
3343.34	...	tr	1	...	...	IV A
3343.76	K	6	2	1	...	III E
3344.7	...	tr	1	...	...	IV A
3344.91	...	1	2	1	...	III A
3346.72	K	7	3	1	...	III E
3347.43	...	tr	1	...	...	IV A

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3348.52.....	....	5	10	8	4	II A
3348.82*....	K	5	2	1	....	III E
3349.02.....	K	20	6	2	....	III Er
3349.41.....	K	40r	10	8	3	II Er
3350.53.....	....	2	2	tr	....	IV
3352.06.....	K	1	....	....	....	V E
3352.3......	....	1n	1	....	....	IV
3352.92.....	K	6	15	12	10	I A
3353.82.....	....	1	1	....	....	IV
3354.0......	....	tr	tr	....	....	IV
3354.64.....	K	60r	60R	50r	20	II
3356.18.....	....	2	3	1	....	III
3357.3......	....	tr	tr	....	....	IV
3357.5......	....	tr	tr	....	....	IV
3358.26.....	K	10	15r	12	12	I
3358.47.....	K	8n	4	1	....	IV
3359.0......	....	tr	tr	....	....	IV
3361.00.....	E	10	15r	12	12	I
3361.22.....	K	} 40r {	8	6?	1	III Er
3361.30*....	....		20r?	10?	10	I
3361.50.....	....	1	2	1	....	III A
3361.82.....	K	10	15r	12	10	I
3362.10.....	K	3	3	1	....	III
3363.60.....	....	2n	1	....	....	IV
3366.17*....	K	5	3	1	....	III E
3366.66.....	....	1	1	....	....	IV
3367.87.....	K	3n	3	1	....	III
3369.05.....	....	1	6	3	tr	III A
3369.20.....	K	2	....	....	....	V E
3370.42.....	K	40r	40r	30	20	II
3371.44.....	K	80R	80R	60r	30	II
3372.20.....	K	5	tr	....	....	V E
3372.59.....	....	1	1	....	....	IV
3372.80.....	K	30	10	7	2	III Er
3372.9......	....	1	1	....	....	IV
3373.58.....	....	1	1	....	....	IV
3374.34.....	K	2	....	....	....	V E
3374.60.....	....	1	1	....	....	IV
3375.69.....	....	3n	3	1	....	III
3377.48.....	....	20	20r	15	15	I
3377.57.....	....	30r	30R	20	20	I
3379.05.....	....	1	1	....	....	IV
3379.20.....	K	15	15r	10	15	I
3379.43.....	....	1	1	....	....	IV
3380.12.....	....	1	1	....	....	IV
3380.28.....	K	15	6	2	tr	III Er
3381.35.....	....	1	1	....	....	IV
3381.44.....	....	2	1	....	....	IV
3382.30.....	K	15	10	8	4	II
3383.76.....	K	40	10	7	2	III Er
3383.84.....	....	1	1	....	....	IV
3384.67.....	....	1	1	....	....	IV

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities: High Temp.	Med. Temp.	Low Temp.	Class
3385.66	....	12	12r	15	10	I
3385.93	K	40r	40R	30	15	II
3387.31	....	tr	tr	....	....	IV
3387.83	K	15	8	3	tr	III Er
3388.75	K	2	....	....	....	V E
3389.60	....	1	1	....	....	IV
3389.90	....	1n	1	....	....	IV
3390.67	K	10	10	10	2	III
3392.18	....	tr	tr	....	....	IV
3392.71	....	10	10	6	1	III
3392.79	....	1	1	....	....	IV
3393.8	....	1n	1	....	....	IV
3394.57	K	15	8	4	tr	III Er
3398.62	K	8	10	7	1	III
3400.14	E	3	2	tr	....	IV
3402.42	K	3	....	....	....	V E
3403.36	K	4	10	5	1	III A
3405.09	K	5	10	5	1	III A
3407.20	K	4	1	tr	....	IV E
3409.80	K	5	1	tr	....	IV E
3411.67	K	5	4	1	....	IV
3415.99	K	5	4	1	....	IV
3416.95	K	3	1	....	....	IV E
3421.30	....	1	tr	....	....	IV
3423.18	....	2	4	1	....	IV A
3425.1	....	2N	1	....	....	IV
3428.12	....	tr	1	....	....	IV A
3428.95	K	4	6	2	....	III
3430.54	....	1	3	1	....	III A
3430.88	....	2	3	1	....	III
3435.40	E	3	4	2	....	III
3439.30	K	8	8	5	tr	III
3443.64	K	5	8	3	....	III
3444.31	....	15	6	3	....	III Eru
3444.41	....	3	6	3	....	III A
3444.89	....	tr	1	....	....	IV A
3445.55	....	1	2	1	....	III A
3446.6	....	2	tr	....	....	IV
3447.4	....	1n	tr	....	....	IV
3448.25	....	1	4	2	....	III A
3449.87	....	2	5	2	....	III A
3450.75	....	1	4	2	....	III A
3452.42	E	2	....	....	....	V E
3453.66	....	tr	3	1	....	III A
3454.17	....	1	3	1	....	III A
3454.73	....	tr	tr	....	....	IV
3455.37	....	2	2	tr	....	IV
3455.43	....	1	1	....	....	IV
3455.76	....	1	4	2	....	III A
3456.40	K	5	....	....	....	V E
3456.65	....	6	8	5	tr	III
3457.29	....	2	5	3	tr	III A

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3457.49	K	4	7	5	tr	III
3458.01	...	3	6	4	tr	III A
3458.08	E	1	1	...	...	IV
3459.41	...	3	2	1	...	III
3461.50	...	20	6	3	...	III Eru
3462.71	...	1n	1	...	...	IV
3463.03	...	tr	tr	...	...	IV
3463.20	...	1	5	3	...	III A
3465.64	K	1	...	...	...	V E
3466.46	...	1n	1	...	...	IV
3467.26	...	6	12	12	2	III A
3467.64	...	1n	1	...	...	IV
3468.36	...	1n	1	...	...	IV
3469.07	...	1n	1	...	...	IV
3469.37	...	1n	1	...	...	IV
3472.81	E	2	1	tr	...	IV
3476.45	K	3	6	4	tr	III A
3476.99	K	2	...	...	...	V E
3477.18	K	15	4	2	...	III Eru
3478.92	K	6	12	8	1	III A
3480.53	K	12	15	15	4	III
3480.89	K	1	...	...	...	V E
3481.11	...	3	2	tr	...	IV
3481.68	K	3	2	tr	...	IV
3483.99	...	1	8	8	1	III A
3485.69	K	6	10	10	1	III
3489.74	K	4	1	tr	...	IV E
3490.77	...	1	8	8	1	III A
3491.05	K	8	3	1	...	III Eru
3493.27	K	4	12	12	4	II A
3495.73	K	6	12	8	1	III A
3495.94	...	2	10	10	2	III A
3499.10	K	8	12	10	1	III
3500.33	K	4	1	...	...	IV E
3503.76	E	1	10	10	1	III A
3504.78	...	2	4	2	...	III A
3504.89	K	8	...	...	...	V Er
3506.64*	K	8	15	15	10	I
3507.43	K	3	2	tr	...	IV
3509.85	E	1	...	...	...	V E
3510.84	K	10	...	...	...	V Er
3511.64	...	3	12	10	2	III A
3516.84	K	3	4	1	...	IV
3519.94	...	1	8	2	...	III A
3520.25	K	8	...	...	...	V E
3525.16	...	3	3	1	...	III
3530.58	K	1	8	2	...	III A
3535.40	K	10	...	...	...	V E
3537.47*	K	1	?	...	...	IV?
3542.51*	E	3	?	...	...	IV?
3547.01	K	15	12	2	...	IV
3556.17	H	3	1	...	...	IV

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities: High Temp.	Furnace Intensities: Med. Temp.	Furnace Intensities: Low Temp.	Class
3558.51*....	H	6?	4?	1	....	IV
3561.59.....	E	2	....	....	....	V E
3561.92.....	E	1	....	....	....	V E
3564.4*.....	E	1	?	....	....	IV ?
3566.00.....	E	2	....	....	....	V E
3573.72.....	....	6	....	....	....	V E
3574.24*....	....	8	3	?	....	III
3578.25*....	E	3	?	....	....	IV ?
3585.86*....	K	4	?	1	....	III ?
3587.13.....	K	4	....	....	....	V E
3595.30.....	R	1	1	....	....	IV
3596.05.....	K	10	....	....	....	V E
3598.71.....	K	15	10	6	1	III
3601.16.....	H	1	1	....	....	IV
3601.37.....	H	1	1	....	....	IV
3603.86.....	E	2	8	3	....	III A
3604.30.....	K	8	10	8	2	III
3606.06.....	K	1	1	....	....	IV
3606.81.....	E	4	10	6	1	III A
3607.12.....	K	2	2	....	....	IV
3609.61.....	E	1	3	....	....	IV A
3610.20*....	E	12	10	8	2	III
3612.25.....	K	2	2	....	....	IV
3613.75.....	K	1	5	1	....	IV A
3614.20.....	K	3	2	....	....	IV
3617.21.....	E	1	tr	....	....	IV
3619.45.....	K	1	1	....	....	IV
3620.00.....	H	1	1	....	....	IV
3623.10.....	E	3	3	....	....	IV
3624.84.....	K	8	....	....	....	V E
3625.22.....	E	1	tr	....	....	IV
3626.09.....	K	4	10	8	1	III A
3626.92.....	K	1	tr	....	....	IV
3632.00.....	E	3	1	....	....	IV
3633.45.....	E	5	3	....	....	IV
3635.20.....	K	8	10	10	5	II
3635.47.....	K	80r	100R	50	40	I
3637.97.....	K	10	10	10	5	II
3640.33.....	E	1	tr	....	....	IV
3641.33.....	K	10	....	....	....	V E
3642.68.....	K	80r	100R	50	40	I
3644.46.....	K	1	1	....	....	IV
3644.69.....	K	4	3	....	....	IV
3646.19.....	K	12	15	15	12	I
3653.49.....	K	100r	125R	60	50	I
3654.58.....	K	15	20	20	15	I
3658.14.....	K	20	25	25	20	I
3659.75.....	K	4	....	....	....	V E
3660.62.....	K	12	15	15	12	I
3662.22.....	K	4	....	....	....	V E
3666.56.....	H	1	tr	....	....	IV
3668.95.....	K	15	15	15	15	I

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3671.66	K	20	20	20	20	I
3677.75	H	tr	1	....	....	IV A
3679.68	K	3	3	....	....	IV
3681.23	H	1	1	....	....	IV
3685.19	K	40	5	1	....	IV Er
3685.95	K	2	7	1	....	IV A
3687.38	E	5	10	8	2	III A
3689.89	K	15	15	15	15	I
3694.43	K	10	8	3	....	III
3696.88	K	2	1	....	....	IV
3698.17	K	3	2	....	....	IV
3700.05	K	4n	3	....	....	IV
3701.53	K	1	1	....	....	IV
3702.29	K	10	10	3	....	III
3702.98	K	2	3	....	....	IV
3704.29	K	15	8	6	....	III
3706.22	K	3	....	....	....	V E
3707.53	K	10n	4	1	....	IV
3708.65	K	4n	2	....	....	IV
3709.95	K	20	15	6	2	III
3713.70	E	1	2	....	....	IV A
3715.33	K	3n	2	....	....	IV
3715.79	....	1	2	....	....	IV A
3717.26	....	1	2	....	....	IV A
3717.39	K	20	20	20	20	I
3719.93*	K	?	1?	....	....	IV?
3720.38	....	2	2	....	....	IV
3721.64	K	8	tr	....	....	V E
3722.58*	E	15?	15?	12?	6	II?
3724.59	E	20	15	5	1	III
3725.12	K	20	15	7	2	III
3728.66	R	1	1	....	....	IV
3729.77	K	50r	50r	45	45	I
3733.78	K	4n	3	....	....	IV
3735.65	E	4n	3	....	....	IV
3736.75	E	1	tr	....	....	IV
3738.90	K	5n	4	....	....	IV
3741.06	K	60r	60r	50	50	I
3741.14	K	1	1	....	....	IV
3741.63	E	8	....	....	....	V Eru
3747.80	E	1	1	....	....	IV
3748.07	E	6n	5	tr	....	IV
3752.87	K	80r	80R	60	60	I
3753.63	K	25	30	25	25	I
3754.93	E	1	1	....	....	IV
3756.95	E	1n	1	....	....	IV
3757.68	K	8	....	....	....	V E
3759.30	K	40	5	tr	....	IV Er
3761.33	K	40	5	tr	....	IV Er
3762.33	K	1	1	....	....	IV
3766.46	K	3	6	1	....	IV A
3769.76	K	1	1	....	....	IV

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities			Class
			High Temp.	Med. Temp.	Low Temp.	
3771.64	K	25	30	25	25	I
3774.32	E	1n	1	....	....	IV
3774.63	K	1	8	3	tr	III A
3782.14	K	2	4	1	....	III A
3786.03	K	20	20	15	8	II
3786.27	K	3	2	....	....	IV
3788.80	....	2	10	4	1	III A
3789.28	E	8	10	2	....	IV
3795.87	E	7	7	1	....	IV
3798.29	E	6	6	1	....	IV
3801.07	K	3	2	....	....	IV
3801.55*	E	1	?	?	....	IV ?
3805.13*	K	1	1 ?	....	....	IV ?
3805.48*	K	1	?	....	....	IV ?
3806.04*	H	1	?	....	....	IV ?
3806.45*	H	1	?	....	....	IV ?
3807.22*	H	1	?	....	....	IV ?
3807.78*	H	1	?	....	....	IV ?
3811.33*	K	4	?	....	....	IV ?
3813.39*	K	2	?	....	....	IV ?
3814.86*	K	4	?	?	....	IV ?
3817.65*	E	5	?	?	....	IV ?
3821.74*	K	2	?	?	....	IV ?
3826.95*	E	1	?	?	....	IV ?
3827.45*	E	1	?	?	....	IV ?
3827.62*	E	1	?	?	....	IV ?
3828.17*	K	3	?	?	?	III ?
3829.70*	E	2	2 ?	....	....	IV ?
3833.19*	E	4	1	....	....	IV
3833.66*	E	4	2 ?	1	tr	III
3833.91*	H	3	2 ?	....	....	IV ?
3836.10*	K	1	....	....	....	V E
3836.75*	E	5	1	....	....	IV
3846.39*	E	6n	2	....	....	IV
3848.29*	E	2	1	tr	....	IV
3853.05*	E	10n	2	....	....	IV
3853.74*	E	10n	2	1	....	III
3857.89*	H	2	4 ?	2 ?	....	III A ?
3858.12*	E	15n	6	2	....	III
3860.46*	H	1	?	?	....	IV ?
3861.10*	E	3n	?	?	....	IV ?
3861.74*	H	1	?	?	....	IV ?
3862.84*	E	10n	2	1	....	III
3864.50*	E	2	?	....	....	IV ?
3866.00*	E	1	?	?	....	IV ?
3866.45*	E	15n	6 ?	1 ?	....	IV ?
3867.77*	H	3	?	?	....	IV ?
3868.42*	E	10n	?	?	....	IV ?
3869.32*	H	5n	?	?	....	IV ?
3869.60*	E	2n	?	?	....	IV ?
3870.12*	E	2	?	?	....	IV ?
3873.25*	E	10n	3	1	....	III

TABLE I—*Continued*

λ (I.A.)	Measured By	Arc Intensity	Furnace Intensities High Temp.	Med. Temp.	Low Temp.	Class
3874.16*....	E	2	?	?	....	IV?
3875.29*....	K	20n	8	5	1	III
3877.60*....	H	2n	1	....	....	IV
3881.41*....	E	4	?	?	....	IV?
3882.13*....	H	15n	?	?	?	III?
3882.34*....	H	10n	?	?	?	III?
3882.87*....	H	20n	?	?	?	III?

2599.93–2679.94	These lines are very difficult in the furnace, and may belong to lower classes than here assigned, especially λ 2657. The low and medium temperatures do not give emission lines of such short wave-length. λλ 2641, 2644, 2647, were obtained in absorption with low-temperature vapor, using explosions as a source of continuous radiation.
2896.89, 2901.04, 2902.19	These lines appear as hazy patches in the arc.
2923.62	May be V.
2941.99, 2948.25, 2956.13	This triplet appears in absorption. λ 2942 coincides with enhanced line, which reverses symmetrically in spark. λλ 2948, 2956, are weak in spark, and reverse unsymmetrically.
2969.07	Widens to violet in arc.
2969.37	Blend *Fe*. Furnace line probably all *Ti*.
3000.87	*Fe* line on red side.
3066.36	Blend V in furnace.
3066.52	Concealed by V line in furnace.
3100.67	Blend *Fe*. Probable intensity *Fe* line subtracted.
3110.61	Blend V on red side. Measured by Kilby .674.
3127.43	Faint in arc, concealed by following line.
3130.81	Intensities partly due to unresolved enhanced line to violet.
3219.33	Blend in arc with λ 3219.21.
3260.26	Strong in furnace for enhanced line. May be blend.
3271.63	Blend V in furnace.
3278.96	Blend with preceding line.
3341.87	Probably an unresolved blend with enhanced line which reverses in spark. Furnace line is unaffected by K mixture.
3348.82	Reversal in spark is in wing of λ 3349.02.
3361.30	Difficult blend with λ 3361.22.
3366.17	Enhanced line on red side of furnace line, which measures λ 3366.15.
3506.64	Weakens rapidly below 2100°.
3558.51	Blend *Fe*.

3337.47 3542.51 3564.4 3574.24 3578.25 3585.86	Disturbed by λ 3590 cyanogen band.
3610.20	Blend *Fe*. Probable intensity of *Fe* line subtracted.
3719.93	Probably present in high-temperature furnace only. Coincides with strong *Fe* line.
3722.58	Blend *Fe*. Probable intensity of *Fe* line subtracted.
3801.55 to 3882.87	Furnace lines more or less concealed by λ 3883 cyanogen band. Class is partially determined by absence at low temperature.

DISCUSSION

In addition to the typical arc lines, the variations of which are shown in the table, three types of lines may now be considered.

1. *Enhanced lines.*—The distribution of these is of interest. It is well known that, in general, the spark radiation is strong in the ultra-violet. The increasing richness toward shorter waves of the titanium spark spectrum is a striking feature. A rough count of enhanced lines, which in the crowded portion was by no means complete, gave the following numbers for intervals of 300 A from λ 2700 to λ 4800:

λ	Enhanced Lines
2700–3000	168
3000–3300	127
3300–3600	78
3600–3900	44
3900–4200	38
4200–4500	33
4500–4800	8

Beyond the green the enhanced lines become very scarce.

During the present investigation, spark spectra were photographed on the same scale as that used for the furnace and arc. A comparison of these with the furnace spectra brought out the fact that the ionized atom emits, in the ultra-violet, not only a richer spectrum, but with a lower degree of excitation than is required for enhanced lines in the visible. In the former paper,[1] the difficulty of producing enhanced lines in the furnace was noted. These appeared faintly at 2600°, and were placed in class V, a

[1] *Mt. Wilson Contr.*, No. 76; *Astrophysical Journal*, **39**, 139, 1914.

condition which has been confirmed by plates for the visible region during the present work. The relative ease of production in the ultra-violet does not show a steady increase toward shorter waves, but is localized between λ 3050 and λ 3400, where a great mass of strong enhanced lines occurs, many of which maintain a considerable intensity at 2250°, and are assigned to class III. This response to moderate temperature is borne out by the fact that these lines undergo self-reversal in a strongly condensed spark, showing that the cooler vapor in the envelope of the spark can emit the lines. The reversal is frequently unsymmetrical, being stronger to the red of the absorption line. This behavior is noted in the table after the class number. When the grouping is investigated, symmetrical and unsymmetrical enhanced lines will probably be found to belong in different multiplets. From λ 3400 to λ 3900, while some notably strong enhanced lines occur, their reversals in the spark are narrower, and the increased difficulty in obtaining them in the furnace places them in class IV. In the ultra-violet beyond λ 3000 the enhanced lines, while numerous, are of a more hazy type in the spark, seldom reversing, and difficult of production in the furnace.

It may be seen from the foregoing, that while a classification of only the stronger enhanced lines is made in this paper, a consideration of the types of enhanced lines in furnace, arc, and spark may lead to a classification as definite as that for the arc lines.

The method of suppressing enhanced lines by mixing with the titanium in the furnace a substance of lower ionizing potential, such as potassium, proved effective, as had previously been found for other elements.[1] Successive photographs of the same exposure time and at the same temperature were made for titanium alone and for a mixture with potassium chloride. The arc lines remained unchanged, while the enhanced lines were reduced to a fraction of their former intensity. The enhanced lines from λ 2700 to λ 4300 were affected in this way, and served as a means of selecting the lines of the ionized atom. In two cases, the method detected coincidences of arc and enhanced lines. λ 2941.99 and λ 3341.87 are strong class II lines. They appear in the spark as reversed enhanced lines, which would be classified as III Er. Other members of the

[1] *Mt. Wilson Contr.*, No. 233; *Astrophysical Journal*, **55**, 380, 1922.

arc multiplets to which these lines belong show the usual effect of weakening in the spark with unsymmetrical reversal. The use of potassium left these lines unaffected, and as they can scarcely be exceptions to the general quenching effect, there is little doubt that we have here superpositions of arc and spark lines.

2. *Lines relatively strong in the furnace.*—The lines designated by "A" in the class column, 192 in number, are lines for which the furnace radiation is especially favorable. They are distinct in a strongly exposed arc spectrogram, but in one normally exposed for the bulk of the arc lines, they are absent or very faint, which accounts in large measure for their being passed over in measurements of arc wave-lengths. These lines occur for all classes of furnace lines, and have a fairly even distribution, though especially numerous from λ 2800 to λ 3000.

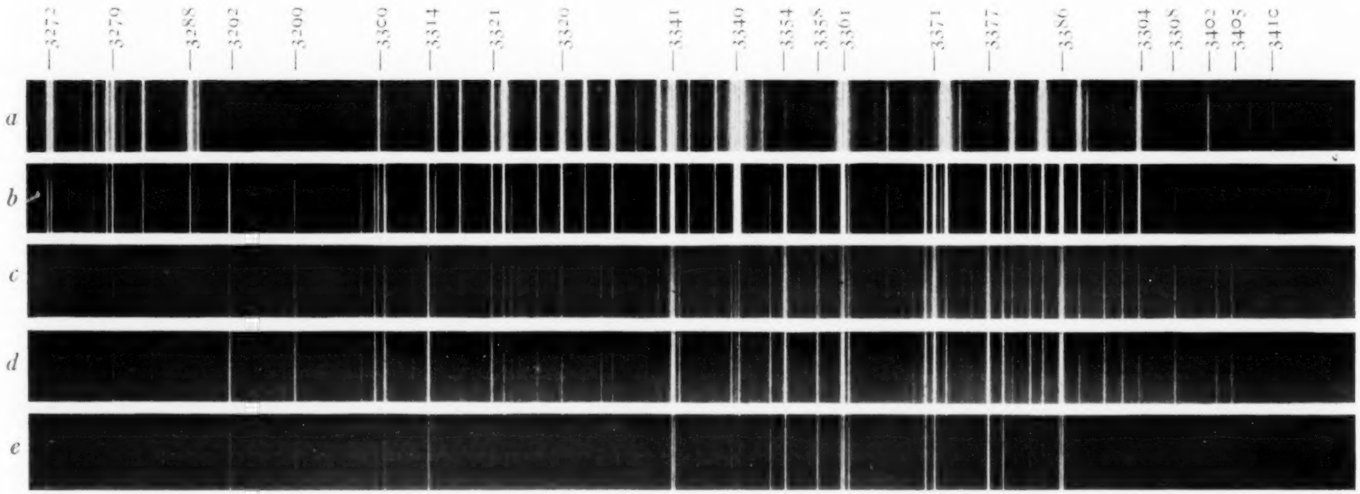
3. *Lines diffuse in the arc.*—These lines, designated by "n" or "N" in the arc column, are difficult to estimate as to arc intensity, and in the more pronounced cases this is not attempted. They often widen unsymmetrically, and the furnace line, which is always sharp, may be near the edge of the hazy arc line. As with other elements, this condition has given improved wave-lengths for such lines when measured in the furnace spectrum, and many of this type are now measured for the first time.

DESCRIPTION OF THE PLATES

Plates V and VI show the titanium spectrum from λ 3130 to λ 3400 for the spark, arc, and three furnace temperatures. Three distinct types of lines are illustrated by the arrangement, which, from top to bottom, is according to descending stages of excitation. These types are, first, the enhanced lines, the stronger of which reverse in the spark and persist through the arc and into the medium furnace temperature; second, typical arc lines, which are usually rather weak in the spark, but hold out in varying degrees as the furnace temperature is lowered; third, lines present in the arc but relatively strong in the furnace. The furnace spectra reproduced were made at temperatures slightly higher than those usually employed. The exposure times for the three stages were 5, 75, and 120 minutes, respectively.

Mount Wilson Observatory
December 1923

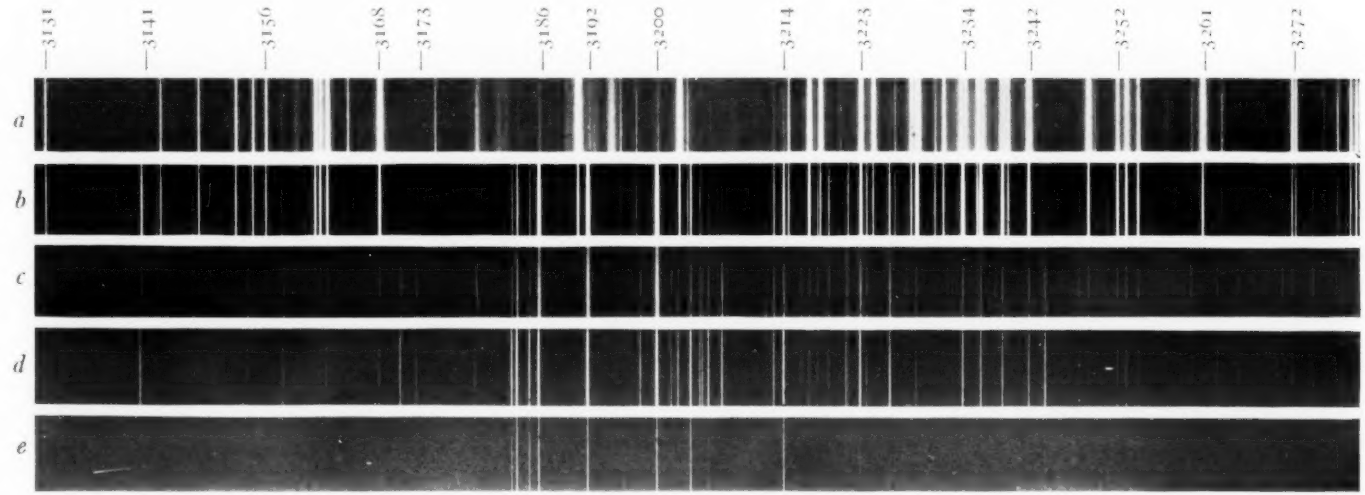
PLATE VI



SPARK, ARC, AND FURNACE SPECTRA OF TITANIUM IN THE ULTRA-VIOLET

a, Spark spectrum *b*, Arc spectrum
c, *d*, *e*, Furnace spectra at 2700°, 2300°, 2100° C., respectively

PLATE V



SPARK, ARC, AND FURNACE SPECTRA OF TITANIUM IN THE ULTRA-VIOLET

a, Spark spectrum *b*, Arc spectrum

c, *d*, *e*, Furnace spectra at 2700°, 2300°, 2100° C., respectively

ON THE BREADTH OF THE HYDROGEN LINES IN STELLAR SPECTRA

By E. O. HULBURT

ABSTRACT

The effect of pressure according to modern theories.—When the Stark theory of the broadening of the Balmer lines of hydrogen is combined with the Saha theory of high-temperature ionization, it is found that in order to account for the broad Balmer lines observed in many stellar spectra, the pressure in the stellar envelope must be as great as several atmospheres. This seems to contradict evidence from other sources which points to much lower pressures. The assumption of a considerable number of free electrons in the atmosphere might explain the discrepancy.

From a consideration of the breadth of the Balmer lines in stellar spectra, it would seem possible to estimate the conditions of the atmosphere of the hydrogen stars. To this end the theory of high-temperature ionization developed by Saha[1] has been combined with the Stark theory of the broadening of the hydrogen lines. Saha's theory has been successful in accounting for many of the important features of stellar spectra, and the view that the broadening of the Balmer lines of hydrogen with pressure or current density is a manifestation of the Stark effect has received additional confirmation from recent work of the author.[2]

Assume pure atomic hydrogen gas ionized by its temperature. Let ν be the total number of hydrogen atoms per cc. If a fraction χ of these are ionized, there are $2\chi\nu$ charged particles per cc. The average distance between the ions is $(2\chi\nu)^{-\frac{1}{3}}$ cm. The positive ions are assumed to be the radiating atoms. Therefore from Coulomb's law of force, each radiating atom finds in an electric field of mean value $e(2\chi\nu)^{\frac{2}{3}}$ electrostatic units, where e is the electronic charge. This result is obtained by assuming that the field is due to a single charge. Actually the field at a point in the gas is the resultant of the effects of a swarm of charged particles of both signs in the vicinity of the point. This indicates that the mean value of the field should be multiplied by a factor σ, which we take to be one-third. The Balmer line radiated by the atom is separated into its Stark

[1] *Philosophical Magazine*, **40**, 472, 1920.

[2] *Physical Review*, **22**, 24, 1923.

components, the separation being proportional to the intensity of the electric field. According to Stark[1] in the case of $H\beta$ the extreme components are displaced 20 A to either side of the parent line by a field of 1.04×10^5 volts, a maximum widening of 40 A. Since the broadened line emanating from the gas is composed of contributions from all the electrical components of a large number of radiating atoms, the average widening may be taken to be a half of this or 20 A. This amounts to a width of 0.06 A per unit c.g.s.e.s. field for $H\beta$. If w is the width of the line in angstrom units

$$w=0.06\sigma e(2\chi\nu)^{\frac{2}{3}}. \tag{1}$$

This calculation is of course not precise; the methods of averaging employed are of the roughest. A more elaborate analysis could be resorted to if necessary, but this would seem hardly advantageous at present because, in the very nature of the problem, orders of magnitude only can be considered significant. We therefore permit this result and those that follow to stand without further qualification. The discussion has borne upon the emission of radiation, but may refer equally well to the absorption of radiation.

Taking ν to be 2.7×10^{19} at 0° C. and atmospheric pressure and replacing e by the value 4.77×10^{-10}, equation (1) becomes

$$w=6000(\chi PT^{-1})^{\frac{2}{3}}, \tag{2}$$

where P is the pressure in atmospheres and T is the temperature on the Kelvin scale.

The reaction isobar of ionized hydrogen atoms in the original form stated by Saha (*op. cit.*, p. 486) is

$$\log_{10}\chi^2(1-\chi^2)^{-1}P=6.851\times10^4\,T^{-1}+2.5\log_{10}T-6.5. \tag{3}$$

Eliminating χ between (2) and (3) yielded an equation in w, P, and T. From this equation values of P in atmospheres were calculated for a series of values of w and T. These are given in Table I. The table refers to the $H\beta$ line. The calculations for $H\alpha$ and $H\gamma$ are slightly different, but the orders of magnitude of the pressures are the same as those for $H\beta$.

[1] *Annalen der Physik*, **48**, 202, 1915.

Although the width of a spectrum line cannot be judged with great accuracy from a reproduction, an examination of certain pictures of stellar spectra published by Sir William Huggins and by the Yerkes Observatory indicated that the widths of the hydrogen lines, either of absorption or emission, were in many cases greater than 20 A and sometimes nearly 30 A, as for example the Balmer absorption lines of α Lyrae. From Table I we see that to produce lines as broad as these would necessitate high pressures or temperatures. Recent evidence, reviewed in a paper by Fowler and

TABLE I

PRESSURES IN ATMOSPHERES

T	w in Angstroms	
	10 A	40 A
5000° K	10^{10} atm.	10^{12} atm.
10,000	10^{3}	10^{5}
15,000	10	10^{2}
20,000	1.3	24
25,000	1.6	14
30,000	1.9	15
35,000	2.2	16

Milne,[1] points unmistakably to the conclusion that the pressures in the reversing layers are low, of the order of 10^{-3} or 10^{-4} atmospheres. This is in serious disagreement with the present calculations. As a further illustration, for 10,000° K and a pressure of 10^{-3} atmospheres, formulae (2) and (3) give a width of 0.07 A for $H\beta$. To obtain a width of 20 A would require a number of charged particles which is 2200 times the number permitted by the Saha formula, or about 1800 times the number of the atoms of hydrogen.

The cause of this discrepancy is not evident. If it is admitted that the pressures in the stellar envelopes are low, we must look for errors in the theory or in the statement of the theory outlined in the foregoing paragraphs. Although equation (1) is not exact, it is difficult to see how it can be in error by several orders of magnitude. The assumption of other and perhaps more potent causes of ionization, such as the absorption of radiation, ionization by

[1] *Monthly Notices of the Royal Astronomical Society*, **83**, 415, 1923.

collision, etc., would not be of much help as long as the pressure is low. The calculation has been made for pure hydrogen. If the easily ionized metal atoms were present, they would supply a large number of charged particles, but even in this case to have a sufficient number the total pressure of the gas would have to be several atmospheres. A possible explanation would be to assume a large number of free electrons. These would produce the broadening without increasing the pressure.

University of Iowa
December 1923

MENSURATIONAL CHARACTERISTICS OF PHOTOGRAPHIC FILM[1]

By FRANK E. ROSS

ABSTRACT

Characteristics of different types of films.—The observation of Cheshire and of Curtis, that photographic film is subject to large and irregular contraction on development, is confirmed only in the case of NC or non-curling film. For motion picture, aerial, portrait, and process film, the contractions and irregularities are found to be considerably less; in the two last mentioned, only one-tenth (about 0.05 per cent) of those found by Cheshire and Curtis. The changes in length and width are different, the length of a film showing increased effect, due probably to strains in the roll. Films of all kinds are subject to parallel changes in length from day to day and from winter to summer, due to humidity conditions. There is no local distortion in portrait film or in motion picture and aerial. Local distortions of $10\,\mu$ sometimes appear in NC film on development, which, however, gradually disappear in a few days.

Photographic film, consisting of a sensitized emulsion coated on a flexible cellulose nitrate support, although available as a commercial product as far back as 1889, has only comparatively recently come into use in scientific investigations. From this slow beginning to widening use and application is inevitable, when the advantages and exact properties of film become better understood. To mention only a few cases of its adaptability to scientific problems, aerial mapping and astronomical photography of a rapid sequence of events—for example, photographing the flash spectrum during an eclipse of the sun, or photographing the planets through our atmosphere whose optical properties are incessantly varying, requiring a quick succession of photographs, in hope of securing even one in a moment of quiescence, are typical of one class. Another class of cases is furnished by the unavoidable curved focal planes of lenses. One component of this curvature is well handled by film, as in spectroscopic investigations, where precision of focus is essential. To what extent the well-known and generally satisfactory mensurational properties of the photographic plate are sacrificed by the substitution of film is the subject of the present paper. The particular and obvious differences caused by lack of

[1] Communication No. 192 from the Research Laboratory of the Eastman Kodak Company.

flatness of the film or uninvited abrupt changes in curvature, purely a mechanical problem, are to be excluded.

The general mensurational properties of photographic film have been well summed up by Professor R. W. Cheshire[1] as follows:

> . . . . If measured in the wet condition the film exhibits an increase in length of about 0.5 per cent. On drying, it shows an immediate decrease of about 0.2 per cent and eventually a decrease of about 1 per cent; furthermore, diurnal variations in the overall length of a film amounting to 0.75 per cent have been observed. The local distortions amount to 5μ or 6μ as a maximum, but these can be eliminated by subsequent washing. If two pieces of film are taken from the same spool, the images formed on them may differ by as much as 0.1 per cent in overall length. The kind of accuracy obtained with film does not approach that obtained with plates.

From the description subsequently given of the film used in the experiments by Professor Cheshire, it may be inferred that what is known as NC film had been employed. This is of importance, as will subsequently appear.

A short investigation of the behavior of film has recently been made by Dr. H. L. Curtis.[2] As in the experiments just cited, NC film was used. By comparing the length of a scale 35 cm long scratched on a mirror, with its length measured on a film upon which the scale had been printed by contact, very irregular contractions, varying between 0.3 and 1.3 per cent, were found. In addition, Curtis states:

> Some work has been done to show the effect of varying the developing and drying processes. The only variation that has given positive results is the use of alcohol for hastening the drying process. This appreciably increases the amount of shrinkage but the variation in shrinkage is not greatly changed.

In 1919 the writer began a series of measures on process film. This is similar to the portrait film, and is characterized by its great thickness, of the order of 0.009 inches (0.22 mm), which is twice that of non-curling film, and 50 per cent greater than motion-picture film. Measurements of the process film were made simultaneously on three samples, 4 inches square, all from the same box, the reference marks being fine holes pierced through the film

[1] *Optician and Scientific Instrument Maker*, **65**, 288, 1923.

[2] "Note on the Shrinkage of Photographic Film," *Jour. Opt. Soc. Amer and Rev. Sci. Instru.*, **7**, 275, 1923.

near each corner. After measurement, two of the pieces were put through the regular development, fixing, and drying operation, and immediately remeasured. They were subsequently remeasured at average intervals of three days during the following month, then at more irregular intervals up to the present time. The individual measures are shown in Figure 1, which gives the average of the

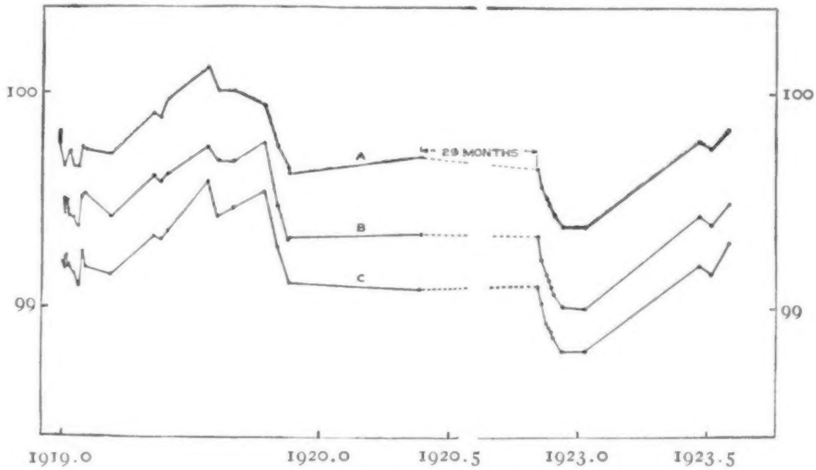


FIG. 1.—*A* and *B*, developed process film; *C*, undeveloped process film

length and width measurements. The contraction on development (after drying) is too small to be well shown in the diagram. It was as follows:

Piece	Percentage Contraction	
	Length	Width
A.............	0.063	0.060
B.............	0.018	0.017

These contractions are of the order of one-tenth of those found on non-curling film by Cheshire and by Curtis. Thus, if measurement be made soon after drying, it appears that the dimensions can be relied upon to this order of accuracy, namely, one-twentieth of 1 per cent. But the subsequent history of these films, as shown in the diagram, indicates that this accuracy does not persist, changes

as great as 0.2 per cent occurring in the course of a few days, and a much greater change from winter to summer, the latter amounting to 0.5 per cent. There is, however, very little secular or progressive change exhibited by these films, the amount being of the order of 0.2 to 0.4 per cent in four years, in the sense of a contraction. Passing to the undeveloped film *C* in the figure, it is seen that it exhibits the same tendencies as the developed, responding equally to humidity and seasonal conditions. This would indicate that the developer (in this case pyro) was without influence, although it must not be taken as conclusive evidence that the composition of the developer is without effect. It did not seem worth while to investigate developers, for it would be difficult to separate any real effect, if present, from the normal large irregularities inherent in the film. Undoubtedly alcohol, which is a solvent of the residual high-boiling solvents and softeners in the film base, produces an abnormal effect (see p. 187), but, so far as I am aware, this ingredient is only used in developers compounded for the developing-out papers.

Relation of width to length contraction.—It is of practical importance to know whether there is any systematic difference between the contraction in the length and in the breadth of a piece of film. Obviously the length and breadth can only be specified in the case of roll film or motion-picture film. However, in the case of the sheets of process film studied above, the length, by which is meant the length referred to the roll from which the sheets were cut, was known in advance to be the long side of the cut sheets. It was found during the course of the long series of measurements plotted in Figure 1 that there was a systematic difference between the changes in length and breadth. The complete series of measurements gave the ratio 0.80, the contractions in the direction of the length being the greater. This difference was verified by measurements of the film in the wet condition. Thus after soaking for 24 hours in water and measuring immediately, it was found that the length had expanded 1.12 per cent, the width 0.81 per cent, giving a ratio of 0.73. This difference is probably due to some weakness developed in the length, caused by unavoidable stresses in this direction in the operations of handling the long rolls.

Influence of the support.—Thus far the film, with its cellulose support and sensitive emulsion, has been considered as a whole. It is of interest to know the relative importance of its two components in determining the behavior. To obtain information on this point, four films were measured at various stages, two being uncoated cellulose base and two coated with emulsion. The following table shows the contraction after being put through development.

	Thickness	Contraction
	(mm)	Per Cent
Uncoated base	0.08	0.32
Uncoated base (aged)	0.08	0.12
Coated film (non-curling)	0.12	0.47
Coated film (aged base)	0.09	0.21

There is thus little doubt that the base controls the behavior. Measurement of these samples for an extended period showed parallel daily and seasonal fluctuations.

Humidity effect.—The correlation between changes in dimensions and humidity has already been shown diagrammatically in Figure 1, the apparently irregular fluctuations shown therein being undoubtedly a humidity effect. In general, a number of specimens of film even of different kinds show corresponding and equal daily fluctuation in length, depending on weather conditions. That this is not a dependable relation, however, is well shown by the following series of measurements of films on two successive days, there being a marked increase of humidity on the second day, so that an increase in lengths was to be expected. Δ is the measured increase of mean dimensions:

	Δ Per Cent
Non-curling film	0.00
Aerial	0.00
Motion-picture positive	0.01
Portrait	0.09

The first three films in this tabulation had been developed but two days previously; the last, eight months previously. Here again irregularities in behavior in the period just following develop-

ment are apparent. The action of the portrait film in expanding under increased humidity is normal, the absence of change in the non-curling, aerial, and motion-picture positive is abnormal. These measures are shown in Figure 2, August 14 to August 15. It will be noted that after August 15 all the films behave alike in response to humidity. This is especially noted in Figure 2 for the measures of September 5, on which date the humidity was abnormally

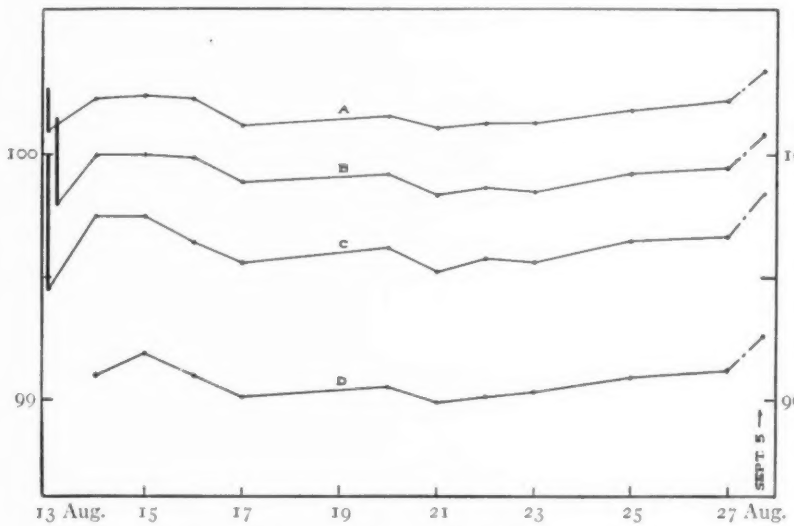


FIG. 2.— *A*, motion-picture film; *B*, aerial; *C*, non-curling; *D*, portrait

high—87 per cent. The changes in all of the films are equal, that of non-curling being somewhat larger.

Effect of alcohol drying on film shrinkage.—Measurements to determine the effect of alcohol drying were made on portrait film, aerial film, and on uncoated film base. Measures were made: (1) before development, (2) after the development, fixing, and washing operation, followed by 12 minutes soaking in alcohol—measurements were made immediately, without giving the film a chance to dry, this being assured by placing the film between glass plates; (3) final measurement after complete drying. The results are given on page 187.

TABLE I

EFFECT OF ALCOHOL DRYING

	Portrait Film		Aerial Film		Uncoated Film	
	Length	Change	Length	Change	Length	Change
	mm	mm	mm	mm	mm	mm
1. Length before development	92.80	....	90.35	....	101.60	....
2. Length after development (wet)	93.54	+0.74	92.36	+2.01	105.10	+3.50
3. Length after drying	92.11	−0.69	88.32	−2.03	94.80	−6.80

The powerful effect of alcohol drying on film disclosed in this table manifestly renders its use prohibitive. This is in contrast to its usefulness and freedom from untoward effects when alcohol is employed in drying photographic plates. The action is, of course, confined to the cellulose base, as may be seen from the table, and is due to the solvent action of alcohol on the softeners contained in the film base. In general, the solubility of the constituents of the film base in water and in the various components of the developing and fixing solutions determines the amount of the development shrinkage.

Variation of development shrinkage over large areas.—In many classes of measurements, general distortion, provided it is uniform, is not a serious matter, the scale being always determined from a set of standard points. Curtis (*loc. cit.*) has shown that over a roll of film 150 cm long the development shrinkage may be sensibly uniform over one roll, while another roll of the same kind of film may show variations of 0.6 per cent over its area or about 100 per cent of the total. The film used by Curtis in his measurements was the non-curling (NC), which has been shown above to be peculiarly subject to the development shrinkage. The measures, of which a summary is given in the table, were made on motion-picture positive film of the standard width of 35 mm, length, 3.1 meters. Sections 100 mm long were measured, uniformly spaced along the film 100 mm apart. Measurement was made as usual before and after development. The resulting shrinkages are given in Table II. The film had been developed August 28. It is seen

that measurements made one day after development (August 29) show local variation in shrinkage of the same percentage amount as were found by Curtis, but in absolute amount are only one-tenth as large. However, this is not the case for the measurements of August 30 and September 5, in which the local variations are seen to have disappeared to a great extent, especially on September 5. The relative humidity on this date was very large (87 per cent), which accounts for the small shrinkage (0.01 per cent). The advantage of delaying measurement in the matter of securing greater freedom from irregularities in shrinkage is obvious from the table.

TABLE II

Section	Shrinkage		
	August 29	August 30	September 5
	Per Cent	Per Cent	Per Cent
1	0.136	0.138	+0.006
2	.118	.106	−0.015
3	.108	.135	−0.014
4	.112	.112	−0.020
5	.158	.120	−0.005
6	.083	.114	−0.007
7	.086	.104	−0.016
8	.127	.117	000
9	.093	.090	−0.008
10	.114	.095	−0.018
11	.093	.094	−0.007
12	.104	.098	−0.010
13	.110	.113	+0.002
14	.130	.105	.000

Distortion within small areas.—It is of importance to know the extent to which film is subject to local distortion. If local distortion is present to an appreciably greater extent than in plates, there undoubtedly would be a serious limitation of its usefulness, in astronomy in particular. The procedure for determining the distortion was as follows:

A *réseau* containing 50 parallel lines spaced one millimeter apart which had been photographed on a plate was printed by contact on the films under investigations, which were then developed and measured as usual. After correcting these measures for general contraction by introducing a linear term, the micrometer readings on the original *réseau* were compared with the readings on the film,

the differences being denoted by v. NC film and portrait film were thus studied. In addition a contact print was made on a Seed 23 plate in order to furnish a suitable basis of comparison. Several series of measures were made on different days on each film, with results shown in Table III. A number of facts are brought to light in this table. The average residual for portrait film is seen to be identical with that for the Seed 23 plate. Moreover, there is no evidence of any systematic run of the residuals. The conclusion is that there is no local distortion of portrait film apparent over a length 50 mm, and accordingly, aside from general distortion, is as suitable as plates for accurate measurement. This does not appear to hold for NC film, where large systematic differences extending over one or two centimeters are in evidence. It is noteworthy, however, that this distortion, so striking in the measurements of May 24 and 25, has practically disappeared in the later measurements. A gradual relief from strain in the film is apparently indicated. The same phenomenon has been verified on another sample of NC film. In view of this tendency to instability for a period of several days after development, it appears to be a good rule to defer measurements of film, whether portrait or NC, until about a week has elapsed. This advantage appears to hold both for general shrinkage (excepting portrait films), for variations in shrinkage over large areas (Table II), and for variations over small areas (Table III). In the case of portrait and process film, apparently identical, deferring measurement would undoubtedly be on the side of safety. There is, of course, the chance of a larger general distortion, but this in general is entirely eliminable in the calculations and must be allowed for in any case.

Secular shrinkage.—On account of the strong seasonal effect, it is difficult to determine the secular or progressive shrinkage of film in the comparatively short period of time covered by the present measurements. One would expect that the progressive shrinkage will not be uniform but will diminish with the time, on account of the presence of low and of high boiling-point solvents in the film base, which evaporate at different rates. Generally speaking, however, this phenomenon has not been observed except in special experimental films, where it has been strongly marked.

TABLE III

LOCAL DISTORTIONS

(Unity = 0.001 mm)

LINE	NC FILM					PORTRAIT FILM				PLATE
	May			June		May		June		
	24	25	28	4	6	25	28	4	6	Seed 23
1	+9	+16	+8	+8	+10	+7	+7	−2	+2	+2
2	+4	+2	−1	−6	+3	−2	−4	−4	−6	−1
3	0	−5	−6	+1	−5	−4	−7	−5	−3	−2
4	+8	0	0	+4	+1	+4	−2	+1	+4	0
5	+4	+4	+3	+5	+2	−6	−5	−5	−4	0
6	+6	0	−1	−1	+2	+1	+4	+5	+3	+3
7	+3	+1	+3	+2	+3	0	+4	−1	0	+1
8	+4	+3	0	0	+1	+2	−2	−1	+2	−4
9	0	−4	−3	−1	−5	0	−2	+1	+2	−3
10	+1	−1	+2	+4	+1	0	+1	+2	0	−3
11	−6	−1	−6	0	−2	−1	−6	+1	+2	−4
12	−1	−3	0	0	−1	+1	+2	0	−1	0
13	−4	−2	+1	−1	0	+5	+1	+1	0	−1
14	−10	−5	−4	−3	−3	+3	−3	+2	−1	+1
15	−12	−7	−8	−6	−5	−4	+1	+1	−2	+2
16	−5	0	−2	−6	−1	+4	0	+5	+2	−5
17	−8	−2	0	−1	+1	+1	−1	+1	+3	+4
18	−5	−5	0	−6	−6	−1	−1	−1	+2	−2
19	−7	−3	−1	−2	0	−1	−4	−3	−2	0
20	−8	−13	−7	−1	+1	−1	−3	+2	−4	−5
21	−7	+1	0	+4	−2	−3	−3	−2	−1	+5
22	−8	−10	−8	−7	−3	−4	−1	−6	−6	−4
23	−6	−4	0	−2	+2	−4	+2	−1	+8	0
24	+2	0	+3	+1	+4	+3	−2	+5	+1	−5
25	−12	−11	−8	−12	−5	−5	−7	−2	−5	−5
26	−4	+5	+4	−1	+1	−1	+4	+3	−1	+3
27	−5	−4	−5	−6	−4	−7	−6	−2	−4	+3
28	−5	+2	0	−2	+2	+4	+5	0	−4	+3
29	−2	+4	+4	+2	+3	+1	+4	0	0	0
30	−10	−1	−1	−6	+1	−2	+6	−3	0	−5
31	−3	+3	+3	−2	0	−5	+1	+4	−1	+3
32	−4	−1	+1	−5	−2	−2	0	0	−3	+3
33	−5	−1	−8	−6	−6	−2	−3	−4	−5	+5
34	−2	−4	−4	−10	−8	−3	−2	−1	−2	−2
35	−2	+1	+3	−1	0	+4	+5	+4	+2	+6
36	+8	+5	+6	+2	+6	−2	−1	−3	−5	0
37	+8	−1	+2	−1	0	+6	+3	+3	+2	+4
38	+5	+4	+5	+1	+6	+3	−2	0	+2	+6
39	+13	+11	+3	+7	+9	+3	+5	+3	0	0
40	+2	+5	−3	−5	−4	0	0	−3	−6	+2
41	+8	+8	+5	+3	+4	+5	+2	+1	+3	+4
42	+3	−2	−3	0	+2	+1	−6	−5	0	−1
43	+4	+3	−5	+1	+1	+3	0	−2	+5	−2
44	+3	−2	−2	+2	+1	−7	−2	−5	−5	−3
45	−1	−5	−5	−1	−1	−1	−4	−4	−3	+3
46	+5	+5	+3	+4	+2	+2	0	0	0	−3
47	+2	+6	+5	+5	0	−1	+3	−2	0	0
48	+4	+2	−1	+2	−1	+5	0	+1	+5	−2
49	+7	+7	+7	+7	+2	−1	−2	+2	−2	+8
50	+1	0	+4	+4	+2	−2	+5	+4	+2	+3
51	+3	+8	+2	+13	+2	+2	−3	−1	0	+6
Average	3.1	4.1	3.2	3.8	2.8	2.6	3.0	2.4	2.5	2.7

There is no suggestion of progressive shrinkage in Figure 2, the period covered being nearly a month. In Figure 1, covering a much longer time interval, there is indicated a possible progressive shrinkage of about 0.2 per cent for the first year only, the following three years showing no change. These facts, however, cannot be considered proved, as is obvious from the figure. Users of motion-picture film find a well-marked progressive shrinkage varying in amount according to the conditions of storage. It appears quite likely that the films in rolls, and thus not ventilated, are subject to progressive changes more than small pieces of film loosely kept and well ventilated as in the present experiments, so that under such circumstances a strong progressive shrinkage is to be expected. In order to preserve dimensions unaltered for a period of years, it is undoubtedly better to keep film in a loose condition in a ventilated chamber. If a closer approximation to predevelopment dimensions is desired, it would be well to place the film in a humidity chamber for a few days before measurement, under a humidity slightly higher than existed at the time of the photographic impression. In addition, to minimize the development shrinkage, the times of development, fixing, and washing should be reduced to a minimum.

Rochester, New York
September 1923

NOTICE OF SKAGGS'S CARD OF JULIAN DAYS FOR 1924

We have received from Mr. J. H. Skaggs, 830 Athens Avenue, Oakland, California, a very convenient calendar for the Julian Days for the year 1924, handsomely printed. Mr. Skaggs is a member of the American Association of Variable Star Observers, and has issued this for the benefit of his fellow-members and for such astronomers as would find it useful. We presume that he will be glad to furnish copies to astronomers who may apply for the calendar.

The Editors

REVIEWS

Handbuch der Spectroscopie. Siebenter Band. Erste Lieferung. By H. KAYSER and H. KONEN. Leipzig: S. Hirzel, 1924. Pp. 498+x. Figs. 1. $7.50.

The many friends of Professor Kayser will be glad to see that in spite of great difficulties he has been able to bring out the seventh volume of his monumental work on spectroscopy. This is the first of three parts in which the volume will be issued. Professor Konen, who also assisted in the preparation of some of the earlier volumes, and who succeeded Professor Kayser on his retirement as head of the department of physics at Bonn, has collaborated in the work. The part before us was completed for publication in 1921, but could not be issued at that time. The two other parts, however, will appear very shortly, as the manuscript was completed in September, 1923. A supplemental chapter will be added to the third part to bring Part I up to the same date.

The present volume follows very closely Volume V as to form and content, and covers the period since 1910. As in Volumes V and VI, the chemical elements are dealt with in the alphabetical order of their symbols, the literature being given for each element at the head of its section. The references are numbered to follow consecutively those in the fifth volume. This Lieferung covers the elements from argon through iron, that is, from "A" through "F," and contains also a section on the spectrum of the air, followed by a brief note on the spectrum of lightning, and three pages on the spectrum of the aurora.

The authors follow their practice of making this a critical work, and do not hesitate to say what they think about the accuracy of the observations which they compile. Thus they express disapproval of the identification by J. Stark of the positive rays of the spectrum of nitrogen, and its supposed coincidences with the spark and arc lines of nitrogen, but they accept Vegard's conclusions that the negative band spectrum of nitrogen is present in the aurora. It would seem that the band spectrum from both the positive and negative poles is found in the aurora, and Vegard in his latest papers considers that the principal line of the auroral spectrum at λ 5578 is in some way due to nitrogen, although the line

has not yet been produced in the laboratory. It is interesting to note that Vegard's latest determination of the wave-length of this line agrees with the determination by Slipher published in this *Journal* (**49**, 266, 1919) which is about 6 A greater than the mean from the observations of the earlier investigators.

The authors accept the evidence furnished by J. W. Nicholson on the basis of his numerical calculations that the strong nebular line or pair at λ 3727 is due to an element other than nebulium, for which he suggested the name "archonium," and for which an atomic weight of slightly less than 3 was derived theoretically. A place is therefore given to this hypothetical element under that name.

The reviewer is gratified to note that the authors do not adopt the name "Aldebaranium" for the element first named by Urbain as "Neo-Ytterbium." There was a dispute as to priority between Auer von Welsbach and Urbain in regard to the separation of Ytterbium, and Kayser in his Volume VI decided in favor of Welsbach as to the discovery but not as to the name. The reviewer takes this opportunity to throw a belated brickbat into the controversy. It is nothing less than ridiculous for the discoverer of an element to give it a name filched from another branch of science with which it has not the slightest connection. We protest also against A. von Welsbach's equally misplaced name of "Cassiopeium" for the other component of Ytterbium. It certainly would be natural for anyone reading these names to suppose that there was at least some slight association between the spectra of these elements and that of the star, or of some member of the constellation, whose names are brought down from the heavens for the purpose. Astronomers must insist that chemists discovering a new element shall let the stars alone unless and until they can prove some genuine connection between their spectra. For us, these elements shall be Lutecium and Neo-Ytterbium, as they were named by Urbain, in spite of the fact that Welsbach seems to have had the right, exercised too late and too badly, to preside at the christening.

About one-fifth of the Lieferung is occupied with a summary of the work that has been done on the spectrum of iron in the last decade. The references begin at 115 and close with 275. The table of wave-lengths covers about sixty-six pages, and includes most of the reliable observations made with the grating and interferometer by such skilful observers as Burns, Meggers, St. John, and others, together with determinations of short wave-lengths by Millikan, Sawyer, and others. The gratifying increase in precision during these last ten years, due to the rigorous

precautions taken with respect to the source, is referred to by the authors in the following remark:

> If we look over the whole table, it appears that aside from the regions of the longest and shortest waves, for many hundred lines distributed over the whole spectrum, an accordance has already been attained which guarantees a precision of from one to two thousandths of an angstrom unit. Enough normals of high precision are, therefore, now available for most practical purposes.

The authors refer to J. Hartmann's extensive paper published as Number XIX of the *Mitteilungen*, of the Observatory at Göttingen, in 1916. In this Hartmann attempts to make a thorough overhauling of the Rowland system of wave-lengths, correcting its internal errors by measurements with the interferometer by Fabry and Buisson. We are glad to call attention to this paper by Hartmann covering seventy-eight pages, as its circulation has doubtless been much limited on account of the war. It contains tables for the correction of Rowland's standard wave-lengths and for their conversion into the international system. They may be, at times, of considerable use to those working with the Rowland system, although Kayser and Konen express the opinion that in practice these conversions cannot well be made with an accuracy greater than 0.01 A, as given by them in Volume VI of their *Handbuch der Spectroscopie.*

At our request G. E. Stechert and Company, of New York, inform us that they import the volume at $7.50, unbound, which we have since learned is also the export price from Germany.

We congratulate Professors Kayser and Konen that they have been able to add a record of the work of spectroscopists for another decade to the great encyclopedia of practical spectroscopy for which the world is greatly indebted to Professor Kayser.

E. B. F.

Verhandelingen van Dr. P. Zeeman over Magneto-Optische Verschijnselen. Leiden: Eduard Ijdo, 1921. 8vo, pp. xv+341, figs. 24, plates XIV.

This handsome volume consists of a collection of the more important papers contributed by Professor Zeeman to magneto-optics following his brilliant discovery of what has since been known as the Zeeman effect. The book is issued in honor of the twenty-fifth anniversary of Professor Zeeman's discovery, by a committee consisting of Messrs. H. A. Lorentz,

H. Kamerlingh Onnes, I. M. Graftdijk, J. J. Hallo, and H. R. Woltjer. The volume is adorned with a fine photogravure of Professor Zeeman as a frontispiece.

The first paper is the classic announcing the discovery of the Zeeman effect, and is published in Dutch, English, French, and German, as it appeared in contemporary journals in those languages. This paper is followed by eighteen others, in the languages in which they originally appeared. The titles are:

1. "On the Influence of Magnetism on the Nature of the Light Emitted by a Substance";

2. "Doublets and Triplets in the Spectrum Produced by External Magnetic Forces";

3. "Measurements Concerning Radiation-Phenomena in the Magnetic Field";

4. "On an Asymmetry in the Change of the Spectral Lines of Iron Radiating in a Magnetic Field";

5. "Some Observations Concerning an Asymmetrical Change of the Spectral Lines of Iron Radiating in a Magnetic Field";

6. "Weiteres zur unsymmetrischen Aenderung der Spectrallinien in einem Magnetfelde";

7. "Some Observations on the Resolving Power of the Michelson Echelon Spectroscope";

8. "Observations on the Magnetic Rotation of the Plane of Polarisation in the Interior of an Absorption Band";

9. "On the Double Refraction in a Magnetic Field near the Components of a Quadruplet";

10. "Double Refraction near the Components of Absorption Lines Magnetically Split into Several Components";

11. "Solar Magnetic Fields and Spectrum Analysis";

12. "Recherches sur la décomposition magnétique des raies spectrales";

13. "Changement de longueur d'onde de la raie médiane d'un triplet dans un champ magnétique";

14. "The Degree of Completeness of the Circular Polarization of Magnetically Divided Lines";

15. "The Magnetic Separation of Absorption Lines in Connection with Sun-spot Spectra";

16. "Considerations Concerning Light Radiation under the Simultaneous Influence of Electric and Magnetic Forces and Some Experiments Thereby Suggested";

17. "On the Polarisation Impressed upon Light by Traversing the Slit of a Spectroscope and Some Errors Resulting Therefrom";

18. "A Method for Obtaining Narrow Absorption Lines of Metallic Vapours for Investigations in Strong Magnetic Fields";

19. "Magnetic Resolution of Spectrum Lines and Temperature."

This collection of Professor Zeeman's most important papers will be of the greatest convenience to spectroscopists and physicists generally. The book is beautifully printed, and the illustrations are excellent.

F.

L'Astronomie et les Astronomes. By AUGUSTE COLLARD. Bruxelles: G. Van Oest & Co., 1921. 8vo, pp. viii+119.

This book, by the librarian of the Royal Observatory of Belgium, belongs to a series of bibliographies issued for the advancement of science, literature, and fine arts in Belgium. It forms a partial index of the astronomical literature published since 1880, being to some extent a continuation of the well-known *Bibliographie générale de l'astronomie*, by J. C. Houzeau and A. Lancaster. Astronomy is divided into eight sections, and the books are arranged chronologically under each language.

By its limitation to books published through the usual trade channels, this work naturally fails to give a proper record of the actual bibliography of astronomy during the last forty years. Many of the most important works have appeared in the serial publications of observatories or of learned societies, or in scientific journals. For example, but one work is attributed to E. C. Pickering during this period, and that is *Contents of Annals of Harvard College Observatory.* If this were intended to imply that Pickering was the author of all the *Annals*, it would more nearly represent his contributions to astronomy, but this particular part of one of the *Annals* happens to have been included, otherwise his name would have been wholly omitted. Again, Simon Newcomb is credited with only his separate books, most of them popular, without reference to his important contributions in the astronomical papers of the *American Ephemeris.* This limitation thus excludes all the work of the late J. C. Kapteyn.

There is an index to authors at the end of the volume.